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THESIS

APPLICATION OF PRESSURE-SENSITIVE PAINT IN SHOCK-BOUNDARY LAYER INTERACTION EXPERIMENTS

by

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March, 1996

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A new type of pressure transducer, pressure-sensitive paint, was used to obtain pressure distributions associated with shock-boundary layer interaction. Based on the principle of photoluminescence and the process of oxygen quenching, pressure-sensitive paint provides a continous mapping of a pressure field over a surface of interest. The data measurement and acquisition system developed for use with the photoluminescence sensor was evaluated first using an underexpanded jet blowing over a flat plate. Once satisfactory results were obtained, the system was used to examine shock-boundary layer interaction in a blow-down supersonic wind tunnel at Mach numbers of 1.4 and 1.7. Details of the measurement technique, and discussion of the flow fields which were examined, are reported.

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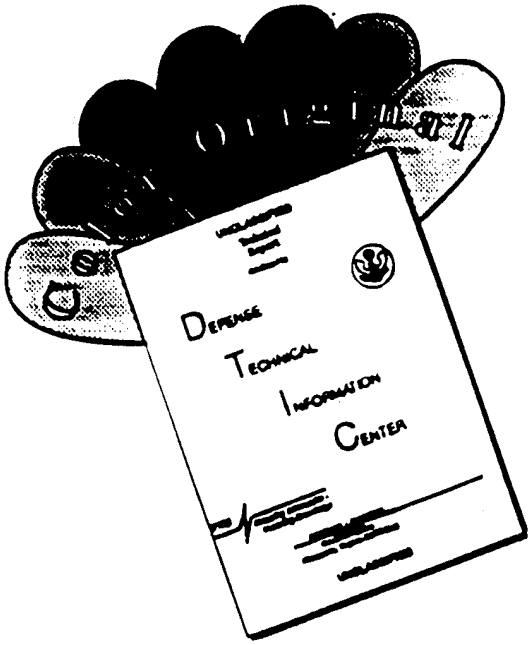

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APPLICATION OF PRESSURE-SENSITIVE PAINT IN SHOCK-BOUNDARY LAYER INTERACTION EXPERIMENTS

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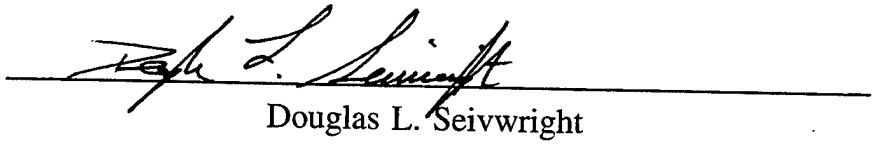
Author: 
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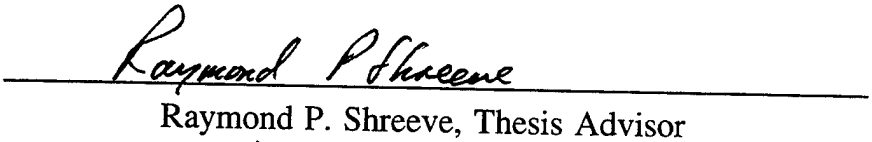
Approved by: 
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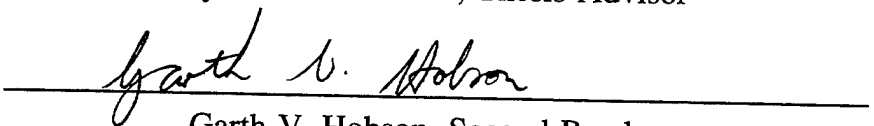
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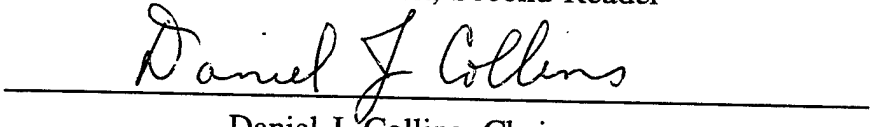
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ABSTRACT

A new type of pressure transducer, pressure-sensitive paint, was used to obtain pressure distributions associated with shock-boundary layer interaction. Based on the principle of photoluminescence and the process of oxygen quenching, pressure-sensitive paint provides a continuous mapping of a pressure field over a surface of interest. The data measurement and acquisition system developed for use with the photoluminescence sensor was evaluated first using an underexpanded jet blowing over a flat plate. Once satisfactory results were obtained, the system was used to examine shock-boundary layer interaction in a blow-down supersonic wind tunnel at Mach numbers of 1.4 and 1.7. Details of the measurement technique, and discussion of the flow fields which were examined, are reported.

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I. INTRODUCTION

One of the major thrusts of military aircraft engine design is towards achieving higher pressure ratios per compressor stage in order to reduce the number of stages and thereby reduce engine weight. This requires higher aerodynamic loading on the blades, and/or higher relative flow velocities over the blading. Where the relative Mach number is supersonic, shock waves will occur in front of and within the blade passages. The interaction of strong shocks with blade surface boundary layers can lead to high losses and reduced turning. Thus shock-boundary layer interaction, and methods to alleviate its attendant negative effects on compressor blade performance, warrant careful investigation. It was the need to make surface pressure measurements in a model simulation of shock-boundary layer interaction in a fan blade passage, which motivated the present study.

Currently, aerodynamic (surface) pressure measurements are made by installing a prearranged distribution of pressure ports in a wind-tunnel model or prototype aircraft. Since the installation of taps is an expensive process, the location and number of taps is normally predicated on a pre-selected area of interest. Obviously, this arrangement offers little flexibility if the area of aerodynamic interest is broad and fine spatial resolution is needed. Even with a substantially instrumented region, the information obtained is spatially discrete. It is often difficult to decide where to position the taps before the model is tested.

Within the last six years, the Central Aero-Hydrodynamic Institute in Moscow, the University of Washington (with support from Boeing and NASA) and McDonnell Douglas Aerospace have independently developed a new technique to measure surface pressures which is based on photoluminescent coatings [Ref. 1 through Ref. 9]. The pressure-sensitive coatings contain photoluminescent probe molecules. With the proper excitation of light, the molecules luminesce with an intensity which is inversely proportional to the local surface pressure. As a result, pressure-sensitive paints offer almost limitless spatial resolution, in addition to being applicable to surface locations which may not be accessible for pressure ports.

A. DESCRIPTION OF THE CONCEPT

Figure 1 illustrates the general concept of the method. A luminescent molecule dissolved in an oxygen-permeable plastic resin is applied to a surface of interest. When illuminated by ultraviolet radiation the coating luminesces with an intensity that depends on the oxygen partial pressure seen by the active molecule. Thus the oxygen partial pressure can be determined from the emitted light intensity and since the mole fraction of oxygen in air is a known constant, the air pressure may then be readily calculated. The result of this oxygen dependence is that the airflow-induced surface-pressure field (and the corresponding oxygen partial-pressure field), gives rise to a luminescence intensity distribution. The intensity field can be imaged using a video camera, the image digitized, processed and stored on a computer. The end result is a map of the surface pressure field.

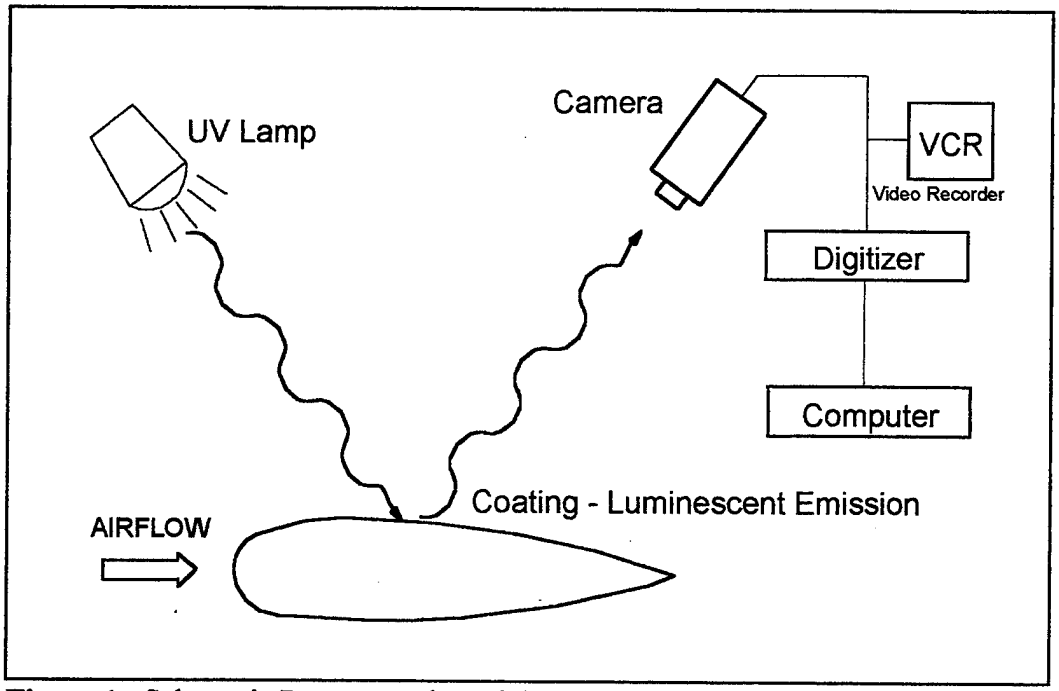

Figure 1. Schematic Representation of the Pressure-Sensitive Luminescent Coating Concept[1]

The processing of the surface pressure image relies on a calibration curve for the coating material, which is based on the Stern-Volmer relation.[Ref. 1: p. 34]

B. APPROACH TO THE PROBLEM

The present work was focused on the development of a working pressure-measurement system, utilizing pressure-sensitive paints, for use in the Gas Dynamics and Turbopropulsion Laboratories at the Naval Postgraduate School. Although the system's initial application was tailored for use in the study of shock-boundary layer interaction in a pilot transonic cascade wind tunnel, and subsequently in a larger supersonic wind-tunnel, its use for other compressible flow studies was anticipated.

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[1] See Ref. 1, page 34, Figure 1

The initial development was carried out using an existing flat-plate model in an underexpanded sonic jet. This was an arrangement that would produce effects similar to those to be measured in the tunnel, (i.e. shock waves impinging on a surface, creating a near-discontinuity in a pressure distribution) but be visually unrestricted since no walls and windows were present. Subsequently, measurements were made of the interaction of the starting shock wave with the side-wall boundary layer in the test section of a blow down wind tunnel. Results were obtained at M=1.4 and M=1.7 using different fixed nozzle blocks. The blocks for M=1.7 were designed and built for the present study, and the design is detailed in Appendix E.

In reporting the work, Section II first provides some preliminary background work done in photoluminescent barometry in addition to the theory of photoluminescent coatings. Section III describes the development program using the sonic free-jet. Section IV provides results of applying the system in the supersonic wind tunnel, and Section V gives conclusions and recommendations. Since the system represents a powerful new tool for two laboratories, the attempt has been made to include all information and details necessary to both use and extend the present system.

II. THEORY OF MEASUREMENT

A. BACKGROUND

Photoluminescence and the process of quenching by oxygen is a photo-chemical interaction that is well documented and reasonably well-understood. In 1980, Peterson and Fitzgerald first recognized its potential as a means to make qualitative assessments in flow visualization studies [Ref. 3]. They reported on a technique in which fluorescent dye, when applied to a surface and excited by a blue light, illuminated in varying degrees of intensity, depending on the introduction of nitrogen or oxygen. When nitrogen was injected through a wall static-pressure tap, a bright streak of luminescence, moving in the direction of the surface flow, was observed. The nitrogen, in close proximity to the fluorescent dye, reduced the effect of the quenching (by displacing the oxygen) and allowed the intensity of the luminescence to increase. The introduction of oxygen, on the other hand, enhanced the quenching process and decreased the luminescence, producing a dark streak. This demonstrated that the concept of quenching could be used to acquire surface pressure measurements.

B. LUMINESCENCE

According to the laws of thermodynamics, a system in an excited energy state due to the absorption of radiation, must be such that the reverse process of emission of radiation can occur. If no other process is available to allow the system to return to its initial state,

then emission must take place. Light emission excited by light absorption is called photoluminescence.

Luminescence is a broad term which encompasses both fluorescence and phosphorescence. The basic, underlying difference between these two processes is the time of emission with respect to the end of excitation; fluorescence has a relatively short lifetime, approximately 10^{-9}-10^{-7} seconds, whereas phosphoresence's lifetime persists for 10^{-4}-10^{-2} seconds. It is the phosphorescent emission that was used in the present work to quantitatively measure the static pressure on a surface of interest.

C. ABSORPTION AND EMISSION MECHANICS

Quantum mechanics provides the necessary theoretical tools to describe the absorption and emission processes of light that were previously unexplainable by wave theory [Ref. 10: p. 457]. Instead of considering light as a wave train of infinite length, the radiation is instead composed of discrete photons (or quanta) whose energies are equal to $h\nu$, where h is the universal Planck constant, 6.63×10^{-27} erg sec. The concepts of light being consider as a wave train and that of discrete photons are linked in that the energy of the quantum is proportional to the light excitation frequency, ν . This led to the hypothesis that radiation of frequency ν could not be emitted or absorbed in arbitrary amounts, but only in quanta of energy $\varepsilon = h\nu$. During an emission process following light absorption, less energy release by emission could occur, but would radiate at a lower frequency.

An absorbing molecule can exist in discrete, sharply defined levels in which transitions between states occur in certain definite steps. The lowest of these states is the ground state. States of higher energy are called excited states. There is a large number of possible excited states, but usually only several of those of the lowest energy are produced with visible or ultraviolet light. A simplistic description of the nature of these excited states is that a single electron has been promoted from an orbital occupied in the ground state to an orbital that is vacant while in the ground state.

Figure 2 illustrates several energy levels of an arbitrary molecule which are represented by the horizontal lines. The vertical distance between two of these lines is proportional to the corresponding difference in energy, $h\nu$; the level N represents the ground state. By absorption of light frequency ν_{NF} the molecule is raised to the state F and if no other energy levels exist between N and F, the molecule can return to N only by re-emission of a photon of light of the same frequency. Theoretically this is the simplest case of photoluminescence; it is called "resonance radiation". However, if, as indicated in Figure 2, several other levels C, D, ... are located between N and F, other transitions to C, D, ... can occur, resulting in the emission of spectral lines of frequency ν_{FC}, ν_{FD}, ... These frequencies must be smaller than ν_{FN} and therefore photoluminescence can have no greater frequency or shorter wave-length than the exciting light.[Ref. 11: p. 2] .

1. Perturbation Theory

For a molecule that absorbs or emits quanta of radiation under the influence of an electric field, perturbation theory of quantum mechanics provides the theoretical model

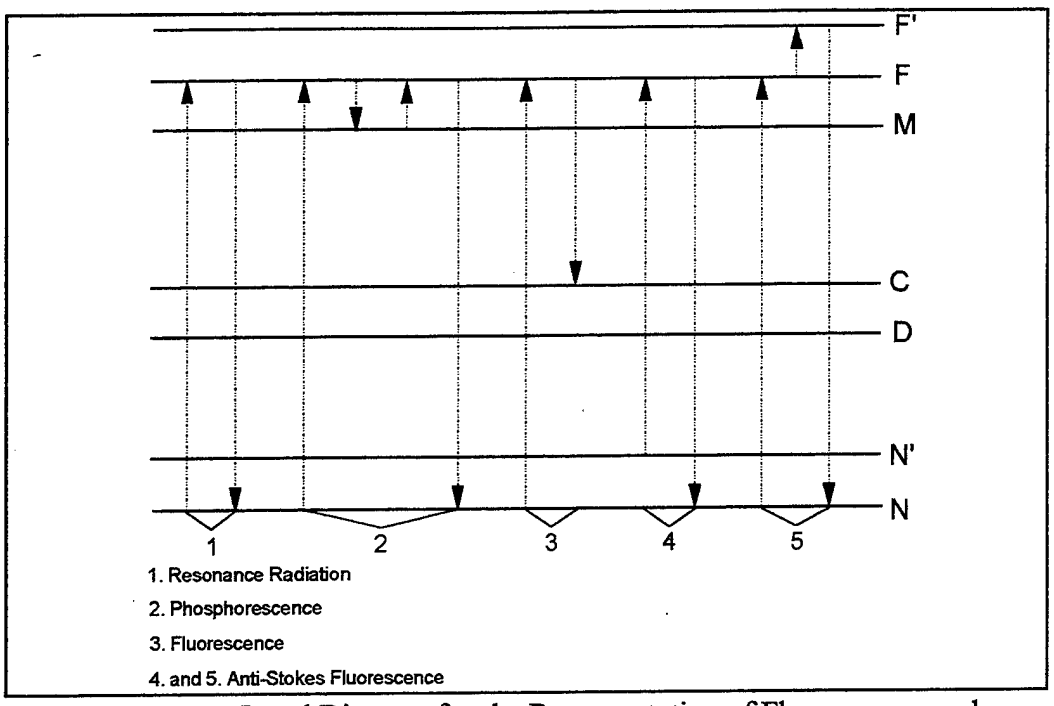

Figure 2. Energy Level Diagram for the Representation of Fluorescence and Phosphorescence[2]

that defines the physical interaction. The general solution of the wave equation for a molecule in the presence of a perturbing field results in certain derived relations that govern the changes of the molecule. One such outcome mandates that for radiation to be absorbed and transition from a stable ground state of energy to an electronically excited state of energy to occur, the frequency of the quantum must be proportional to the difference in energy between the states, a situation previously discussed. Once this condition is met, the probability of the transition is governed by the value of the transition moment integral, a second corollary from the solution of the perturbed wave equation:

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[2]Figure 2 is found in Ref. 11, page 4, as Figure 2

$$m = \int \Psi_u \, \mathbf{M} \, \Psi_l \, d\tau$$

Here, Ψ_u and Ψ_l are the total wave functions for the upper and lower states respectively (the wave functions result from the unperturbed solution of the Schrödinger wave equation) and **M** is defined as the dipole moment operator [Ref. 10: p. 583]. Evaluation of this integral determines the probability of an optical transition between two states. Detailed analysis has shown that transitions are probable only between states characterized by wave functions of a certain class. The results have been summarized in the form of selection rules which are formulated in terms of the quantum numbers that describe the electronic states involved [Ref.12: p. 51].

Perhaps the most important is the rule governing spin multiplicity. This states that the spin of an electron must not change during an electronic transition. As will be seen later, although from a theoretical standpoint transitions between states of different "multiplicity" do not intercombine, in practice they are observed, but the probability is usually much lower than an allowed transition. Thus, selection rules are good empirical guides, but they are not inviolable.[Ref. 13: p. 36]

Although the selection rules considered have been based on the absorption and emission of light by a molecule under the influence of a perturbing field, a second set of selection rules similar to the first but derived under a different set of circumstances govern radiationless processes. These processes, in addition to the spontaneous emission of light, compete with the excited state of a molecule in depleting its acquired energy and allowing it to return to its ground state.

2. Spontaneous Emission

An excited state may undergo a third radiation-related transition to a lower state by means of spontaneous emission, i.e., fluorescence and phosphorescence. In this process, an excited species looses energy in a spontaneous manner in the absence of an electric field. It is a random process: the rate-of-loss of excited species following a kinetic first-order reaction. If a process follows first-order kinetics described by a rate constant "k", the mean radiative lifetime, (the time τ taken for the intensity to fall to 1/e of its initial value), is given by

$$\tau = 1/k$$

When a radiative transition occurs between states of similar multiplicity, it corresponds, according to the selection rules, to an allowed transition. Such transitions are characteristic of fluorescence emission having lifetimes equal to $\tau = 10^{-8}$ seconds. However, there are transitions in which τ is much higher, 10^{-3} seconds. When selection rules suggest a low probability for a transition to occur, such as between states of different multiplicity, the transition, though theoretically forbidden, can occur, but the process is relatively slow. This is representative of phosphorescent emission. [Ref. 10: p. 585]

3. Triplet and Singlet States

In the absence of a magnetic field, the energy of a single unpaired electron characterized by its given values of "n" (the principle quantum number) and "l" (the azimuthal quantum number) must be further refined to explain the observed fine structure of atomic spectra. The additional amount of energy that the spectroscopic evidence

indicates is attributed to the interaction that occurs between the angular momenta from the intrinsic spin and orbital motion of the electron. When several electrons within an atom (or molecule) are present, the resultant orbit and resultant spin angular momenta components can combine in several ways resulting in several energy levels for a single configuration of an atom (or molecule). This interaction is known as Russell-Sanders coupling, the result of which is the "multiplicity" of energy levels that a given electron configuration of an atom may possess. Thus, a single energy level for a given electron configuration for an atom (or molecule) is referred to as singlet state, two energy levels as a doublet, three energy levels a triplet, etc. [Ref.14: p. 79] A more thorough discussion is given in Appendix A.

Nearly all molecules have a ground-state electronic configuration in which the spin of each electron is opposed to, or paired up with, the spin of another electron which otherwise has the same spatial quantum numbers, a consequence of the Pauli exclusion principle. In this instance the total angular momentum of each electron within the pair, composed of the spin and orbital momenta, tend to cancel with each other . When all the pairs of electrons within the molecule are considered, the net result is zero total angular momentum (vector), producing a single energy level for the given electron configuration. Molecules will have, in addition to a ground state that is usually a singlet state, a number of excited states that also have all the electrons paired and that are, therefore, also singlet states. [Ref. 15: p. 16]

Whether or not the ground state is a singlet state for molecules with an even number of electrons, there will be excited states in which a pair of electrons have their spins in the same direction, giving the molecule a net total angular momentum (vector). In this case, the coupling interaction results in three energy levels for the configuration, and thus the designation triplet state.

Therefore, promotion of an electron to an upper state can in principle give rise to two types of energy states, the triplet and singlet, while still maintaining the same electron configuration. Therefore, for every singlet state there is a corresponding triplet state, with the triplet state displaying a lower energy level. Figure 3 illustrates the two types of electronically excited states, where the spin orientations for each state are depicted as arrows next to the appropriate state. The additional lines within each electronic state refer to the various vibrational and rotational energy levels the molecule may acquire with the absorption of energy.

4. Intramolecular Processes Involving Excited States

With the absorption of a quantum, a molecule is raised from a singlet ground to a singlet excited state. The selection rules stipulate that the absorption of electromagnetic radiation does not "unpair" the electrons of a molecule (transitions occur between states of like multiplicity) thus preventing direct absorption of light from a singlet to a triplet state. The molecule, having been raised to an upper vibrational level within the excited state, begins to lose the excess vibrational energy by collisions with surrounding molecules. The

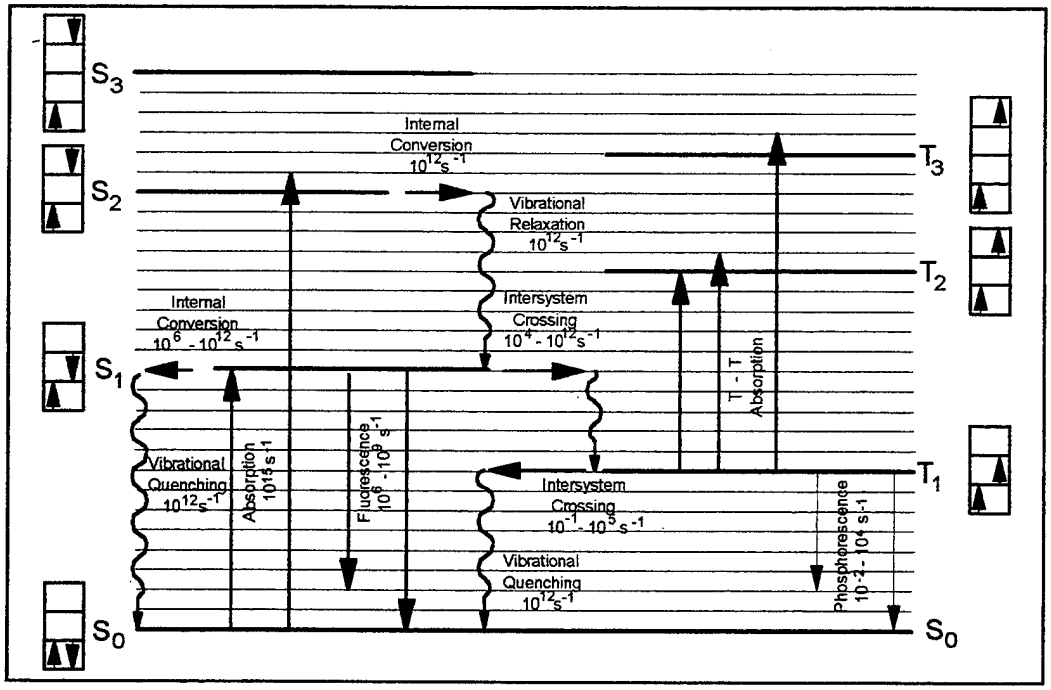

Figure 3. Energy Levels of Molecular Excited States and Transitions Between Them[3]

radiationless process of internal conservation then occurs whereby the molecule passes from a low vibrational level of the upper state to a high vibrational level of a lower state having the same total energy. Once internal conversion is complete, this cycle of events repeats itself leading to the net result of the molecule falling to the lowest vibrational level of the first excited singlet state as illustrated in Figure 3. [Ref. 15: p. 9]

At this point, the molecule may return to the ground state by one of three paths:

$$S_1 \rightarrow S_o \text{ (Internal conversion)}$$

$$S_1 \rightarrow S_o + h\nu \text{ (Fluorescence)}$$

$$S_1 \rightarrow T_1 \text{ (Intersystem crossing)}$$

---

[3] Figure 3 is found in Ref. 16, page 71, as Figure 5-1.

The internal-conversion process, involved with the intramolecular energy transfer between the first excited singlet and ground state, takes place at a much slower rate (10^{-9} seconds) as compared with the same process occurring between the upper excited singlet states to the first excited singlet state (10^{-12} seconds). The increase in inefficiency in energy transfer is explained by the relatively large energy separation between S_1 and S_o as compared to the energy differences between the upper excited states. This allows fluorescence (10^{-9} to 10^{-7} seconds) and, with the combined effect of the spin-forbidden nature of the states, the process of intersystem crossing (10^{-9} seconds) to effectively compete with the internal conversion process.

When a molecule returns to the ground state via the first excited triplet state, it undergoes a conversion process known as intersystem crossing. Intersystem crossing is a non-radiative process between states of different multiplicity. It is theoretically forbidden with regard to the formal selection rules, but in practice, these transitions do take place (although with extremely low probability). This is made possible through the "breakdown" of the spin-orbit coupling model discussed in Appendix A. In the absence of magnetic or electric fields the total angular momentum of the molecule remains constant, and the ability to discern between specific states such as singlet and triplet is possible. However, when an electromagnetic field is present, though the total angular momentum vector remains constant, the spin and oribital degrees of freedom become time dependent, and it becomes meaningless to speak of specific states [Ref. 16: p. 12]. This ultimately leads to the mixing of states. The interaction is enhanced by heavier elements

due to an increase of the magnetic field developed by the nucleus, as in the case of platinum octaethlyporphyrin (PtOEP).

The lowest vibrational level of the lowest triplet state is generally situated at an energy level below that of the lowest excited singlet state, but its upper vibrational levels reach to the bottom of the singlet level, and intersystem crossing occurs with the molecule crossing over to one of these upper vibrational levels of the lowest triplet state. From here the molecule rapidly looses its excess vibrational energy and falls to near the lowest vibrational level of the triplet state.

Again, the molecule may return to the ground state from this point by one of the following paths:

$$T_1 \rightarrow S_o \text{ (Intersystem Crossing)}$$

$$T_1 \rightarrow S_o + h\nu \text{ (Phosphorescence)}$$

As before, it might be expected that the analogous process of intersystem crossing from the lowest vibrational level of the triplet state to the ground state would take place with equal facility as the transition from $S_1 \rightarrow T_1$. In fact it is usually some 10^6 - 10^9 times slower. If radiationless $T_1 \rightarrow S_o$ transitions occurred with rate constants of 10^{-8} seconds, the molecule would have no time to emit $T_1 \rightarrow S_o$ phosphorescence by the spin-forbidden radiative process. On the other hand, if the $S_1 \rightarrow T_1$ intersystem crossing process were as slow as that of the $T_1 \rightarrow S_o$ radiationless process, then it could not compete effectively with fluorescence. Phosphorescence would then be a rare phenomenon and the photochemical behavior would be very different. The difference between the rates of the

$S_1 \rightarrow T_1$ and $T_1 \rightarrow S_o$ radiationless processes is, as was the case with internal conversion, a function of the energy differences between S_1 and T_1, and, T_1 and S_o.[Ref. 15: p. 41]

D. OXYGEN QUENCHING

The exceptionally long radiative lifetimes of molecules in the lowest triplet state make them vulnerable to a variety of radiationless processes that deactivate the molecule, allowing it to return to the ground state. As an example, they are very susceptible to collisions with molecules, and in such cases may encounter molecules of a specific nature which are particularly effective in removing excitation energy.

Previous reference was made to the fact that most molecules with an even number of electrons have a ground state in which their electrons occupy orbitals in pairs. These molecules were said to have singlet states. There are however some molecules containing an even number of electrons for which the states of lowest energy have two unpaired electrons occupying different orbitals. The most important of these is molecular oxygen, of which the ground state is a triplet. Molecular oxygen is very effective in removing triplet excitation energy, and can act at exceedingly low concentrations. [Ref. 15: p. 36]

The energy transfer that takes place when an excited triplet PtOEP molecule collides with a triplet oxygen results in a ground-state singlet PtOEP molecule and a singlet excited oxygen molecule. The reaction is expressed as follows:

$$T_1 + {}^3O_2 \rightarrow S_o + {}^1O_2$$

The reaction occurs very rapidly but is consistent with the formal selection rules. It is this bimolecular reaction that results in the quenching of the phosphorescence. The University

of Washington found that when PtOEP was embedded in an oxygen-permeable silicon resin and subject to atmospheric pressure, the quenching reaction had a rate comparable to that of phosphorescence. Variations in atmospheric pressure from 0 to 1 atmospheres demonstrated a suitable drop in phosphorescence yield of PtOEP that would allow it to be useful as a measurement tool in the study of static pressure changes in aerodynamic wind tunnel testing. [Ref. 9: p. 18]

E. MATHEMATICAL MODEL DEVELOPMENT

Oxygen quenching of luminescence by collisional deactivation of the emission process is the basis for developing a prediction model. It is important to note that the end result of this development, the Stern-Volmer relation, is strictly valid only for free molecules in solution. However, it has been found that it describes accurately the quenching process that occurs in the present situation. The basis for the present development is the work of Parker [Ref. 15], which may be consulted for further details.

The development first begins with the definition of the triplet formation efficiency, ϕ_t, being the number of triplet molecules formed per quantum of exciting light absorbed. Assuming now that a system, illuminated with a beam of exciting light of constant intensity, is in a photochemically steady state. The rate of population of the lowest excited singlet state, S_1, is found to equal the rate of light absorption, I_o, and the rate of formation of triplet molecules by crossing from S_1 is equal to $I_o\phi_t$.

Figure 4 illustrates the rates of the various processes by which the triplet is produced and consumed; these are represented in equation form as follows:

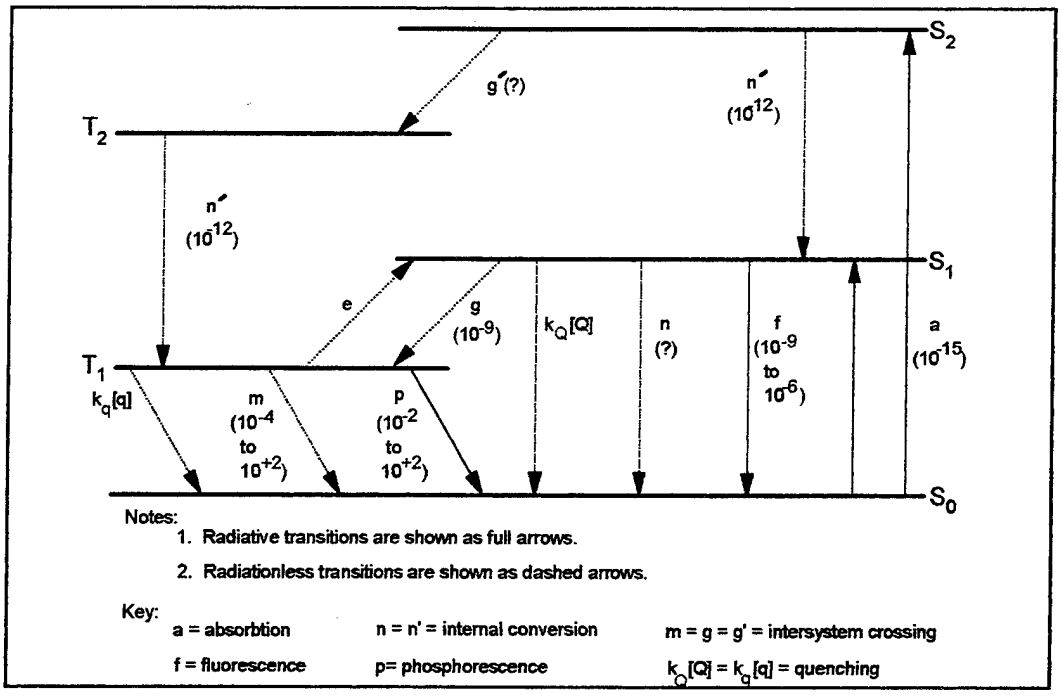

Figure 4. Summary of Transition Types and Associated Rates[4]

$S_o \xrightarrow{h\nu} S_1 \rightarrow T_1$	Rate = $I_a\phi_t$ (Triplet Production)
$T_1 \rightarrow S_o + h\nu$	$k_p[T]$ (Phosphorescence)
$T_1 \rightarrow S_o$ + heat	$k_m[T]$ (Intersystem Crossing)
$T_1 + q \rightarrow S_o + q$	$k_q[T][q]$ (Triplet Quenching)
$T_1 \xrightarrow[\text{Activation}]{\text{Thermal}} > S_1$	$k_e[T]$ (Intersystem Crossing)

The square bracketed [q] and [T] represent concentrations. [q] represents the concentration of all quenching impurities in the system, $k_q[q]$ a composite pseudo first-order rate constant for impurity quenching, and $k_e[T]$ represents the rate of thermal activation of triplet molecules back to the excited singlet level [Ref. 15: p. 87].

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[4]Figure 4 is found in Ref. 15, page 69, as Figure 23

[T] represents the concentration of excited triplet molecules when the steady state has been achieved. All processes so far considered in Figure 4, with the exception of light absorption, are first-order reactions having rate constants equal to the reciprocals of the lifetimes quoted.

Now consider, in addition to the previous statements and definitions made with respect to the steady state of the system, that the rate of production of excited triplet molecules (in state T_1) is just balanced by their rate of disappearance via the various processes discussed above. This can be expressed as

$$I_a\phi_t = (k_p + k_m + k_q[q] + k_e)[T] \qquad (1)$$

Since the rate of emission of phosphorescence is $k_p[T]$, the phosphorescence efficiency ϕ_p is given by

$$\phi_p = k_p[T] / I_a \qquad (2)$$

Equation (1) may be solved for I_a and substituted into equation (2) to arrive at

$$\phi_p = k_p\phi_t / (k_p + k_m + k_q[q] + k_e) \qquad (3)$$

In the absence of quenching agents affecting the removal of triplet excitation energy, equation (3) gives, for the phosphorescence efficiency,

$$\phi_p^\circ = k_p\phi_t / (k_p + k_m + k_e) \qquad (4)$$

Taking the ratio of equations (3) and (4):

$$\phi_p^\circ/\phi_p = 1 + k_q[q] / (k_p + k_m + k_e) \qquad (5)$$

or,

$$\phi_p^\circ/\phi_p = 1 + K[q] \qquad (6)$$

where

$$K = \tau_o k_q \text{ and } 1/\tau_o = (k_p + k_m + k_e) \qquad (7)$$

Equation (6) is known as the Stern-Volmer equation for quenching, and the constant K as defined in equation (7) is referred to as the Stern-Volmer quenching constant.

For this particular application, the quenching impurity, [q], may be defined as

$$[q] = S\, P_{O_2} \qquad (8)$$

where S is the solubility of oxygen in the system and P_{O_2} is the partial pressure of oxygen in equilibrium with it. This leads to the relation

$$\phi_p^\circ/\phi_p = 1 + K'\, P_{O_2} \qquad (9)$$

Finally, by definition, the luminescence, I, is linearly proportional to the quantum yield (ϕ = photons emitted/photons absorbed) for a given quenching condition, (i.e.,$I = I_{abs}\phi$) , where I_{abs} is the excitation light intensity by the luminescent species. Thus

$$I_{max}/I = 1 + K'\, P_{O_2} \qquad (10)$$

where I_{max} is the maximum possible value that occurs in the absence of a quencher.

1. Temperature Effects

The effect that temperature has on the efficiency of phosphorescence may lead to a decrease in the intensity by several orders of magnitude over the range of 77° K to room temperature. The effect results in the long lifetime of triplet states and the correspondingly greater susceptibility to impurity quenching and intersystem crossing [Ref. 15: p. 89].

The rate constants for each of the intramolecular processes depend on temperature, following the Arrhenius equation,

$$k = A\, e^{-E_a / R T},$$

where k is the rate constant, A is the pre-exponential factor, E_a is the activation energy, R is the gas constant, and T is the temperature in degrees Kelvin [Ref. 9: p. 20]. Hence, in equation (10), I, I_{max}, and K are all functions of temperature.

2. Aerodynamic Application

In order to apply the form of the Stern-Volmer relation presented in equation (10), it would be necessary to purge the vicinity of the surface of interest of all oxygen in order to determine I_{max}. In most cases of experimental work, this is impractical. A more convenient approach is to manipulate the governing equation so that determination of I_{max} becomes unnecessary.

Equation (10) is first modified by noting that the oxygen partial pressure, P_{O_2}, is related to the air pressure, P, by $P_{O_2} = X\,P$, where X is equal to the mole fraction of oxygen. Equation (10) then becomes:

$$I_{max}/I = 1 + K' X P \qquad (11)$$

In the method used in the present work, two images are taken. In the "flow-on" case, the pressures are unknown. In the "flow-off" case, the pressure distribution is constant on the surface and equal to atmospheric pressure. These conditions are represented, respectively, as follows:

$$I_{max}/I = 1 + K' X P \quad (12)$$

and $$I_{max}/I_o = 1 + K' X P_o \quad (13)$$

where the subscript "o" denotes the value for the flow-off conditions. Dividing equation (13) by equation (12),

$$I_o/I = (1 + K' X P)/(1 + K' X P_o) \quad (14)$$

Rearranging,

$$I_o/I = 1/(1 + K' X P_o) + [(K' X P_o)/(1+ K' X P_o)](P/P_o) \quad (15)$$

which gives

$$I_o/I = A + B (P/P_o) \quad (16)$$

where,

$$A = 1/(1 + K' X P_o) \text{ and } B = (K' X P_o)/(1 + K' X P_o) \quad (17)$$

A and B represent the coating sensitivity coefficients and are, in general, functions of temperature for both wind-on and wind-off conditions. In the absence of a temperature variation across the surface, A and B have the same value over the whole image. Notice that A + B = 1. This condition occurs only when the images of I and I_o are taken at the same temperature. If any temperature variation is present between the two images, a value other than one will result. [Ref. 1: p. 34] Techniques discussed in Section 3 will outline the procedures used for determining these coefficients.

III. EARLY DEVELOPMENT USING A FREE JET APPARATUS

A. APPARATUS AND FLAT PLATE ASSEMBLY

A sonic-jet nozzle system located in the Gas Dynamics Laboratory (Bldg. 216) at the Naval Postgraduate School was used in the initial experiments. A schematic of the facility is illustrated in Figure 5. A photograph of the jet nozzle is shown in Figure 6.

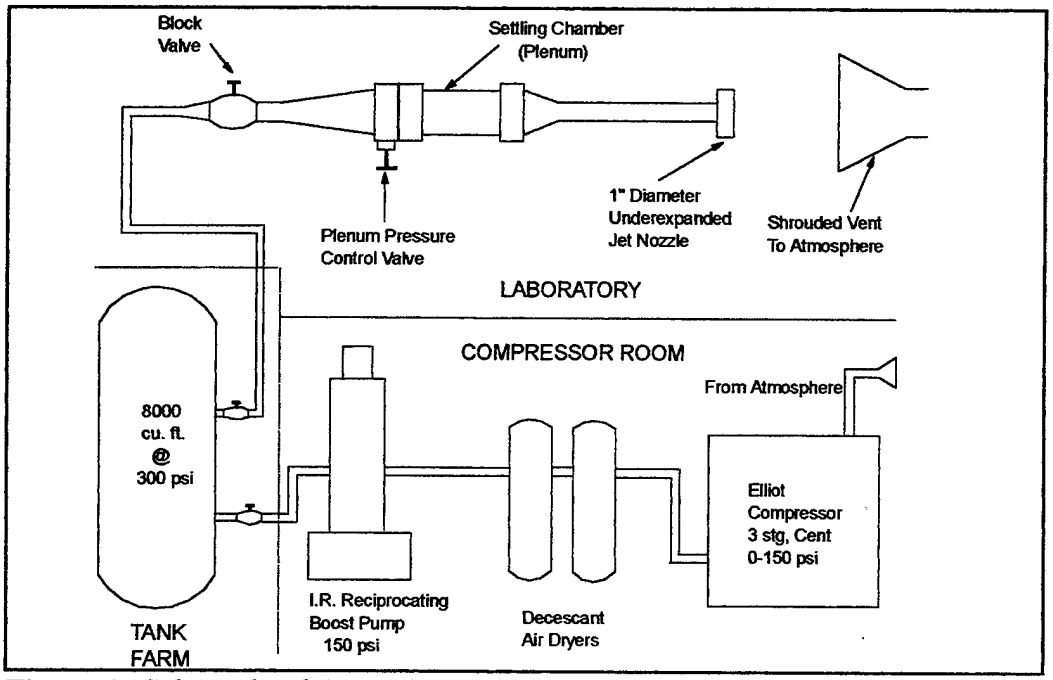

Figure 5. Schematic of the Underexpanded, Sonic Jet Nozzle and Supporting Facility

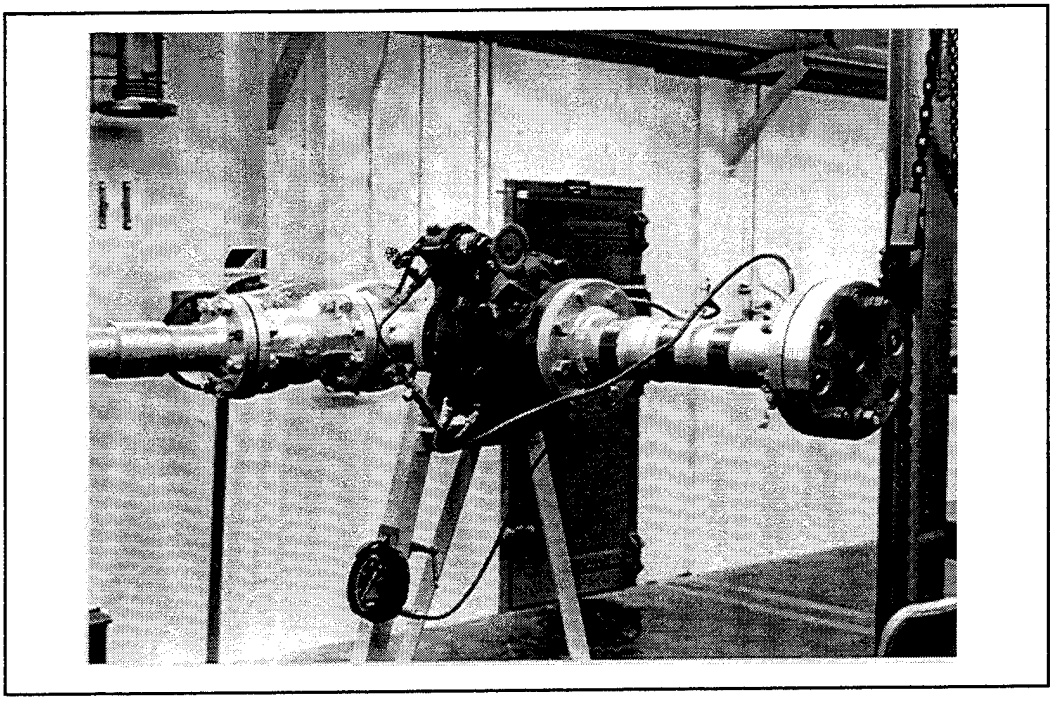

Figure 6. Underexpanded Jet Nozzle Apparatus

The flat plate used in the present work was a model designed and previously used for jet interaction studies in the supersonic wind tunnel. The plate was made of stainless steel with a leading edge diameter of 0.008 inches. Twelve of the existing pressure taps were chosen as close to the centerline of the plate as possible. Figure 7 shows a schematic of the surface of the plate showing the twelve taps relative to the centerline. The pre-arrangement of the taps, in addition to discovering two plugged ports, required that three offset taps be used to maintain near uniform spacing in the streamwise direction.

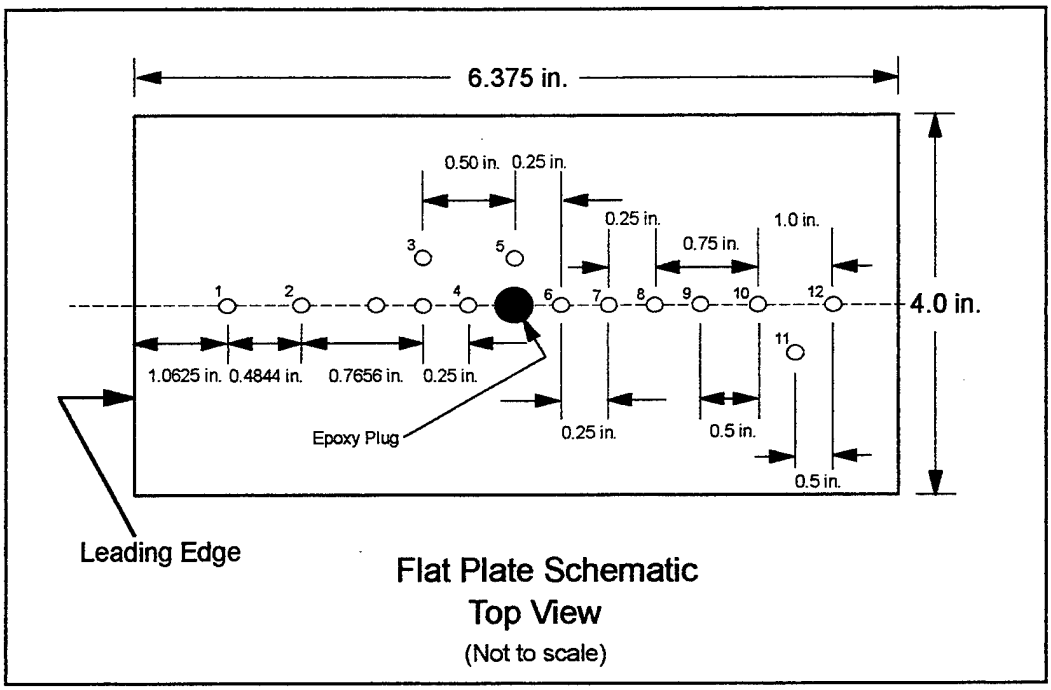

Figure 7. Schematic of the Pressure Port Arrangement on the Plate Surface

A simple bracket was made to mount the model so that the surface of the flat plate become a radial plane, effectively dividing the axi-symmetric jet in half. The bracket and model are shown in Figure 8 while Figure 9 illustrates this assembly mounted to the face of the jet. Plate washers were placed on the mounting bolts to create a 1/4 inch gap between the leading edge of the plate and nozzle face. This was necessary as it was found that the jet would not properly form if the plate were installed with its leading edge at the plane of the nozzle opening. Pneumatic pressure measurements were made using the Scanivalve ZOC system developed by Wendland [Ref. 17].

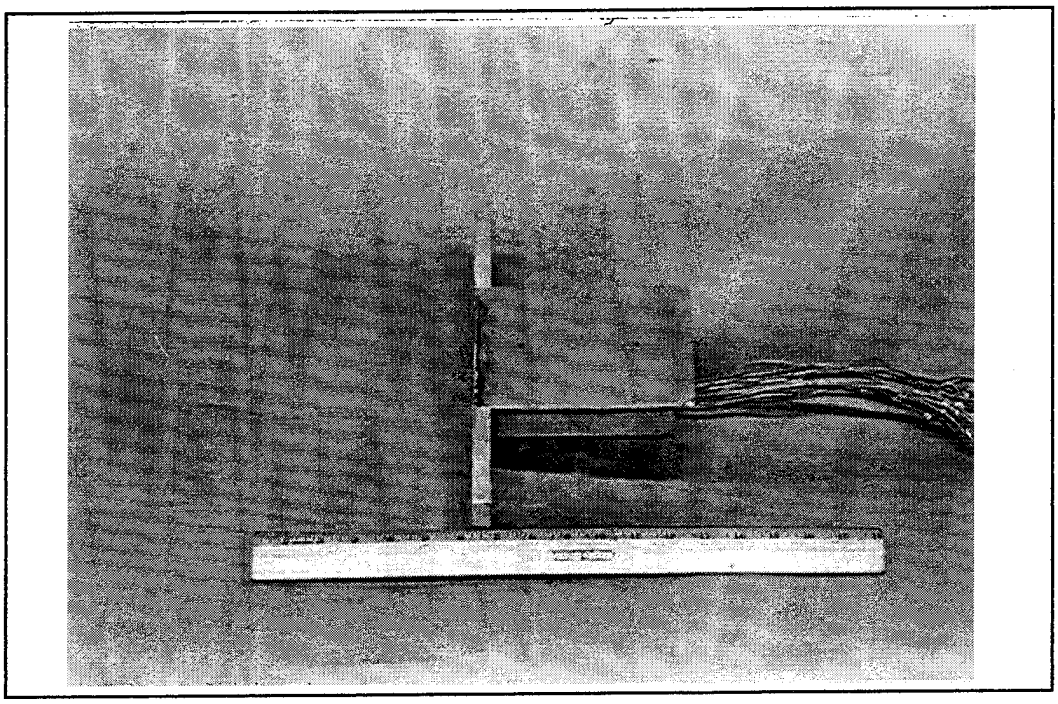

Figure 8. Bracket and Model Assembly

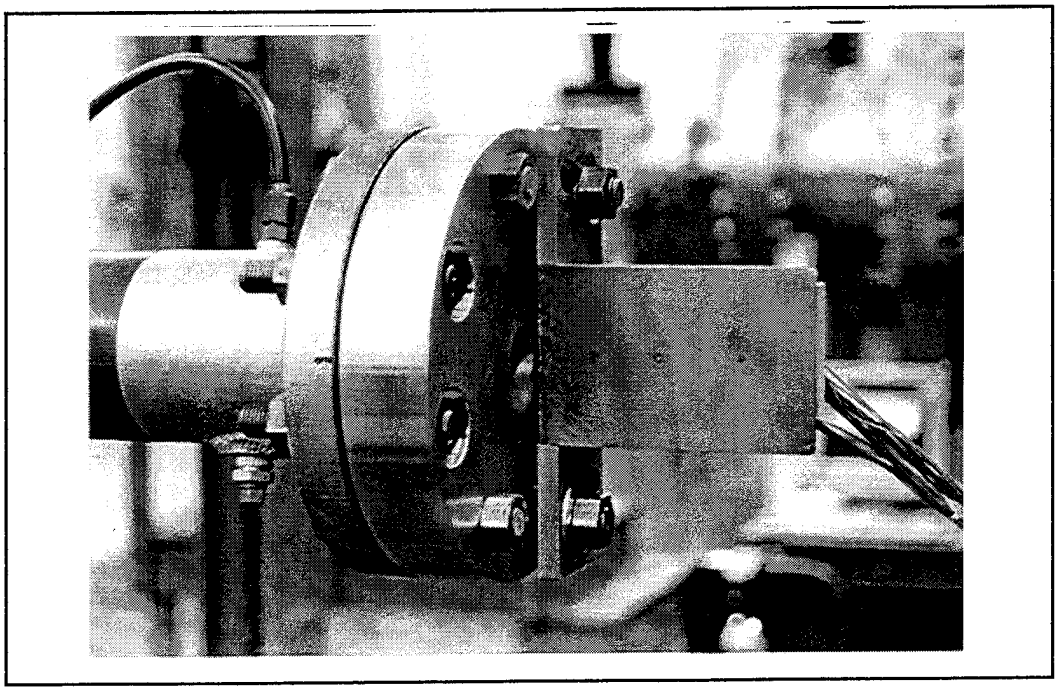

Figure 9. Bracket and Model Assembly Mounted to the Face of the Sonic Jet

1. Freestream Flow Field of the Underexpanded Sonic Jet

The mechanics of formation and structure of an underexpanded jet from a sonic nozzle have been studied in detail by Adamson and Nicholls [Ref. 18: p. 265]. A schematic of the structure is illustrated in Figure 10.

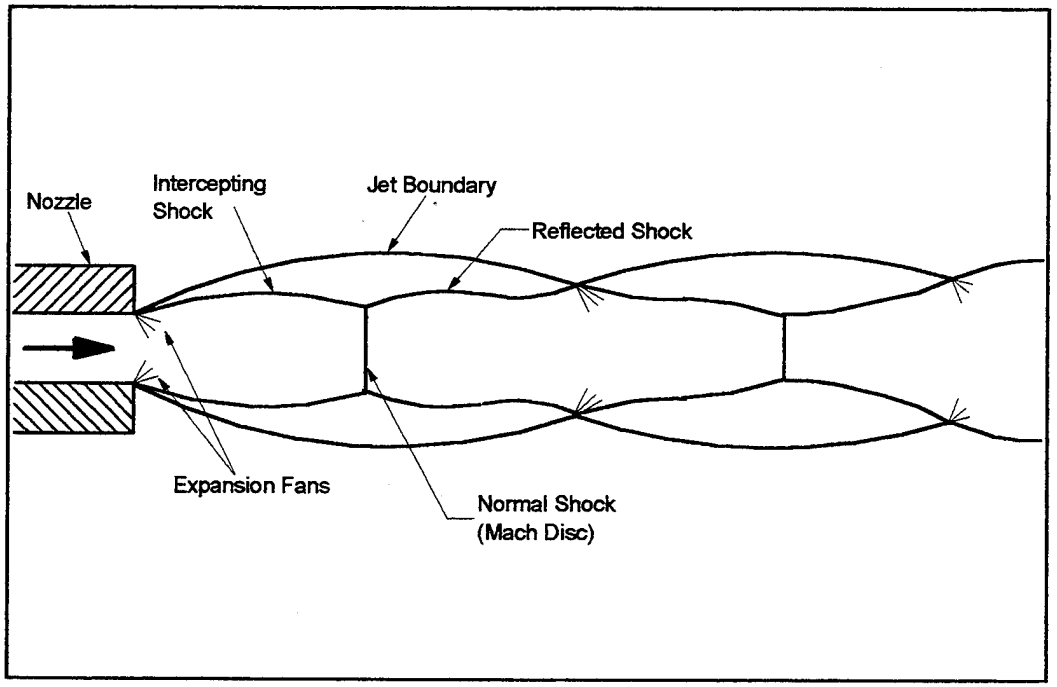

Figure 10. Sketch of Jet Structure Behind a Highly Underexpanded Nozzle[5]

The "Mach disc" within the free-jet offered an event that would produce a pressure discontinuity similar to that of the starting-shock structure in the supersonic wind tunnel, but without the visual restrictions imposed by thick test-section windows.

Using the schlieren technique, visualization studies of the flow field across the flat plate were recorded. The data acquired using the pressure-sensitive paint on the flat plate

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[5]Figure 10 is found in Ref. 18, page 265, as Figure 1

could then be interpreted with reference to the flow structure. These studies began by observing the underexpanded jet without the flat plate mounted to the jet nozzle. This was done to provide a reference for changes in the flowfield as a result of the interaction with the plate. Since the jet structure was axi-symmetric, it was anticipated that, with the plate surface aligned along the centerline of the jet, the plate would simply isolate half of the jet structure. Figure 11 illustrates the jet structure without the flat plate installed at 65 psig plenum pressure. The flow proceeds from right to left.

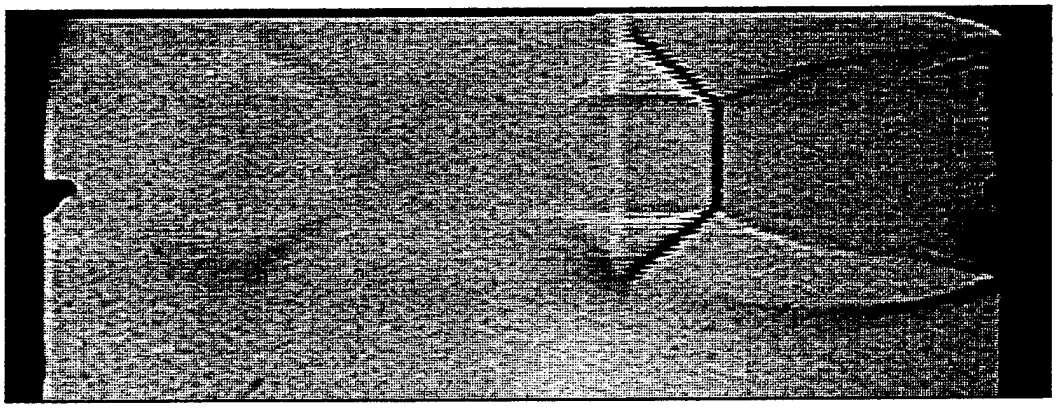


Figure 11. Underexpanded Free Jet at 65 psig Plenum Pressure

The flat plate was then bolted to the nozzle face and several runs were made at varying plenum pressures to record the shock structure. Three specific plenum pressures, 65, 80, and 90 psig were chosen as test points at which to compare pressure measurements with data using the luminescent paint, and the schlieren images of the flow field. The schlieren images of the three events and the corresponding pressure measurements from the orfices along the flat plate are illustrated in Figures 12, 13, and 14.

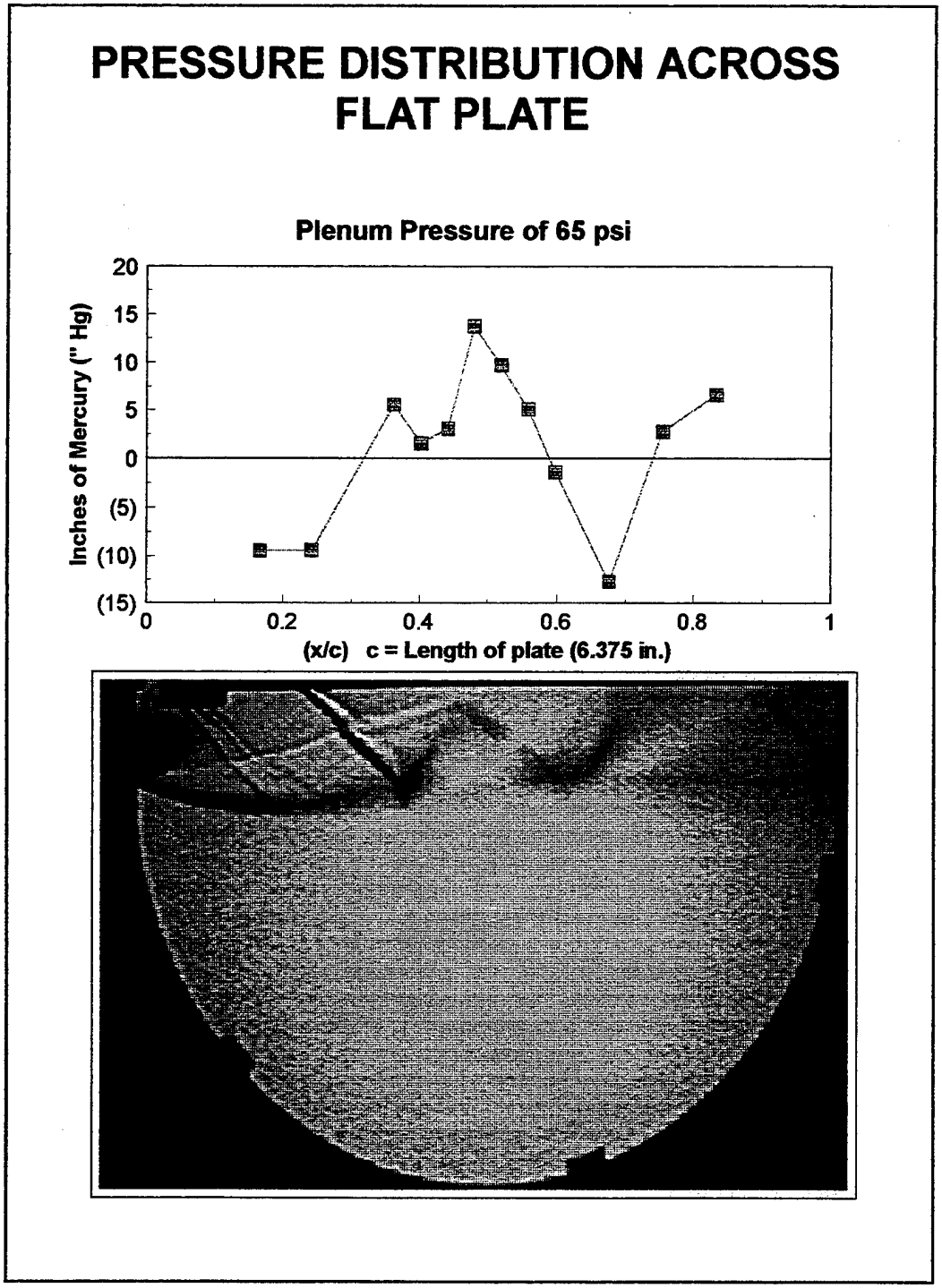


Figure 12. Flow Visualization and Pressure Distribution Across Flat Plate at 65 psig (Flow is from left to right)

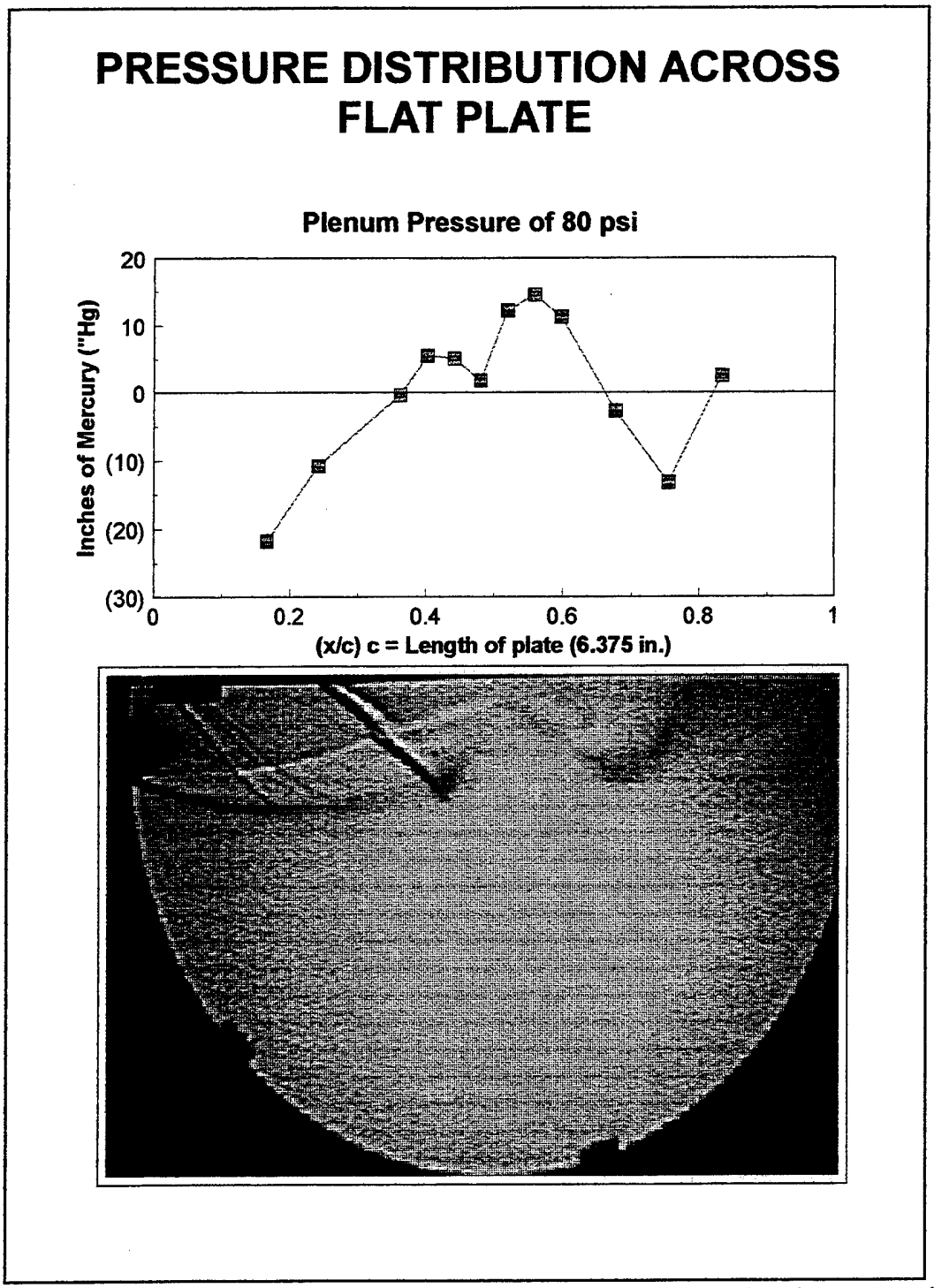


Figure 13. Flow Visualization and Pressure Distribution Across Flat Plate at 80 psig (Flow is from left to right)

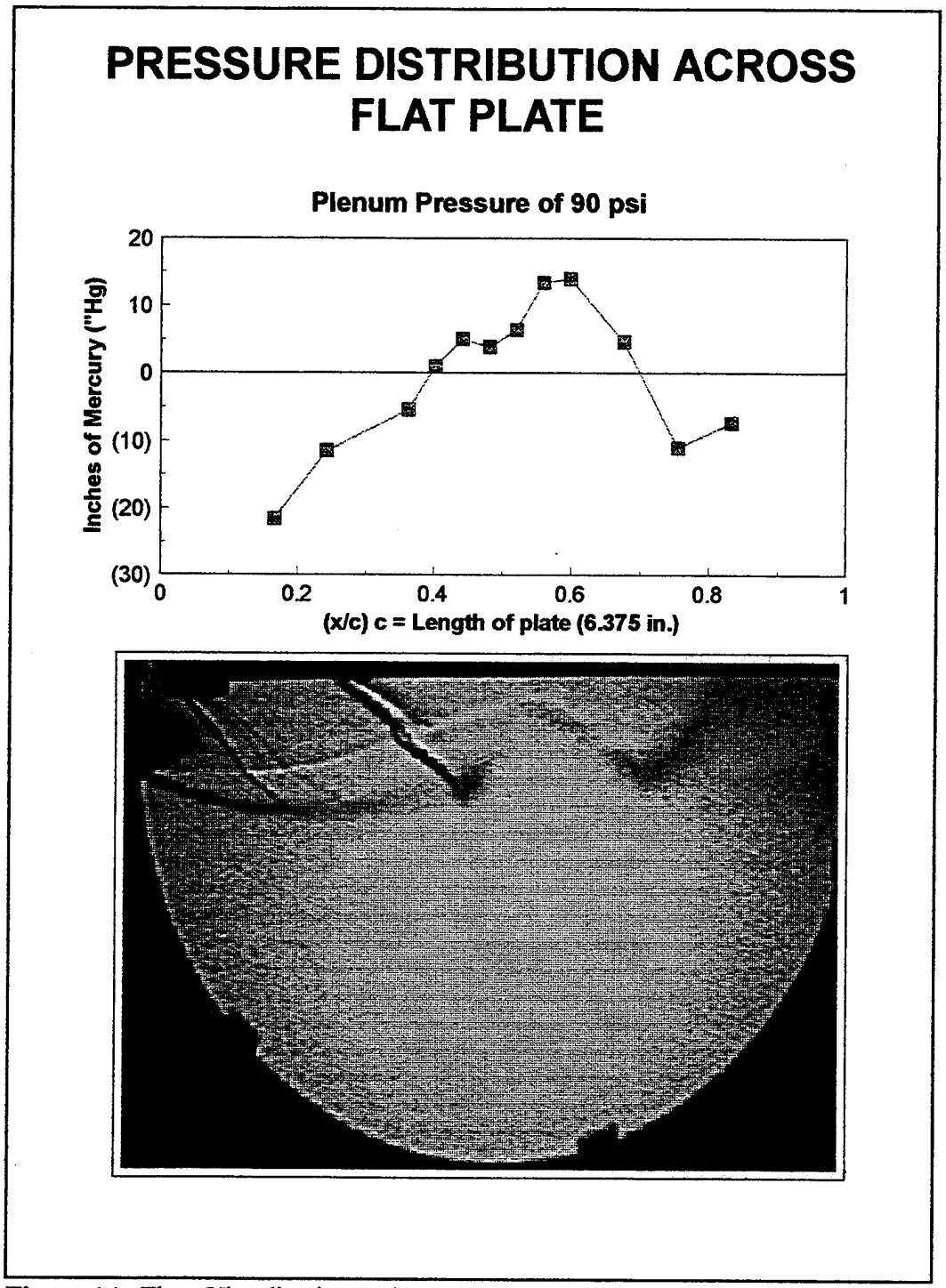


Figure 14. Flow Visualization and Pressure Distribution Across Flat Plate at 90 psig (Flow is from left to right)

The images and the pressure measurement graphs have been aligned so that the pressure changes seen on the graphs correspond to the events occurring on the plate surface.

As can be discerned from the schlieren images in Figures 12, 13, and 14, two oblique shocks appear, a consequence of the plate being placed in the flow field. Figure 15 shows a comparison of the flow fields with and without the plate. The oblique shock emanating from the leading edge of the plate can be explained as being due to the underexpanded process the flow undergoes as it leaves the nozzle. The flow, as it exits

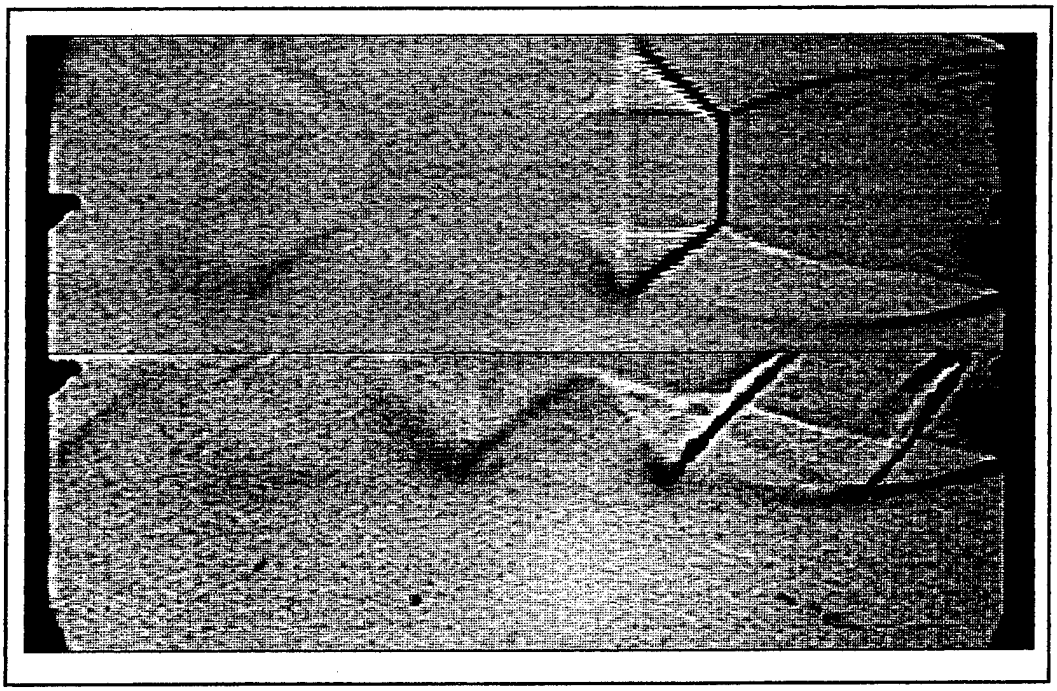


Figure 15. Flow Field Comparison Without (Top) and With (Bottom) the Flat Plate

the nozzle, is off-axis with respect to the centerline of the plate thus encountering the plate at an incidence angle other than zero degrees. The flow in these images is from right to left.

The second oblique shock's structure gives the perception that it extends from the surface of the plate to the jet boundary; however, closer examination of the two images in Figure 15 shows that the oblique shock actually merges with the reflected shock (see Figure 10) giving the erroneous illusion of a single entity. Of greater interest is the extent of the oblique shock to the point of total suppression of the normal shock. The sensitivity of the flow to the plate was much greater than first thought, and it was unclear what events were taking place to justify the magnitude of the oblique shock. Additional study seemed warranted.

a. Further Flow Field Studies

To visualize the flow, methanol was injected through the second pressure port in the plate surface. Several light fixtures were placed around the plate to better illuminate the injection area and to provide contrast between the background and flow field. A video recorder was used to record the events.

Figures 16 through 18 show the sequence of events from selected frames of the video at two different vantage points. In each set of images, the flow proceeds from left to right.

In Figure 16, the plenum pressure was steady at 30 psig -- the boundary layer up to this point remained attached. At 38 psig, Figure 17 shows initial indications of reversed flow at the center of the plate. In addition, 1/2 inch to the left of this point, a pooling of methanol formed. This behavior indicated the presence of a bubble in which a

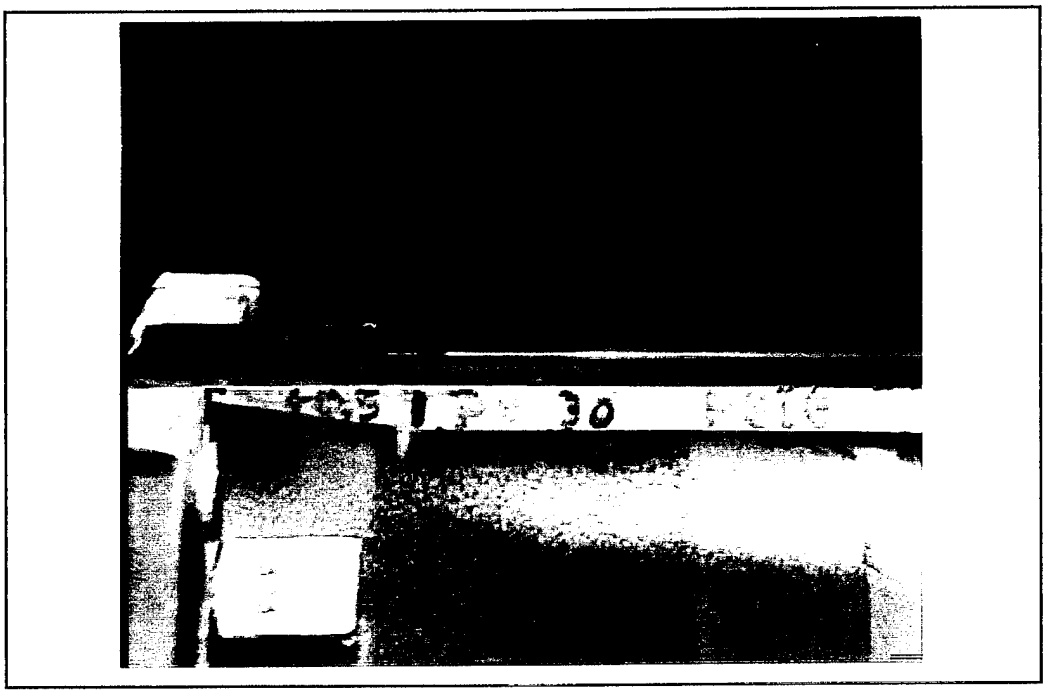


Figure 16a. Flow Visualization at 30psig -- Cross Flow View

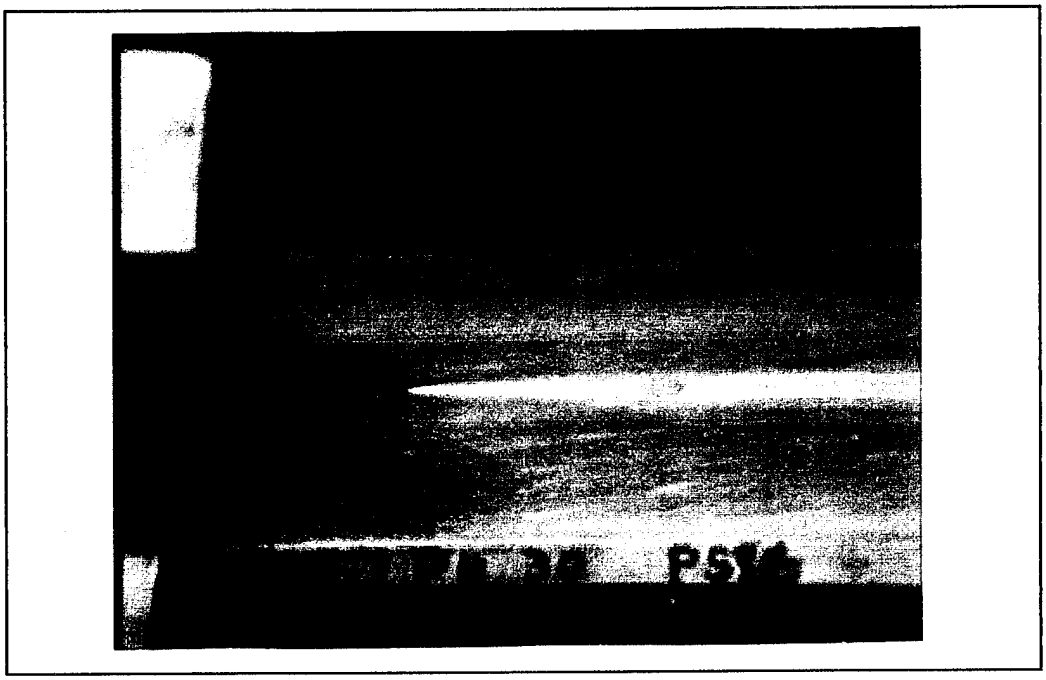


Figure 16b. Flow Visualization at 30 psig -- Acute View

Figure 17a. Flow Visualization at 38 psig -- Cross Flow View

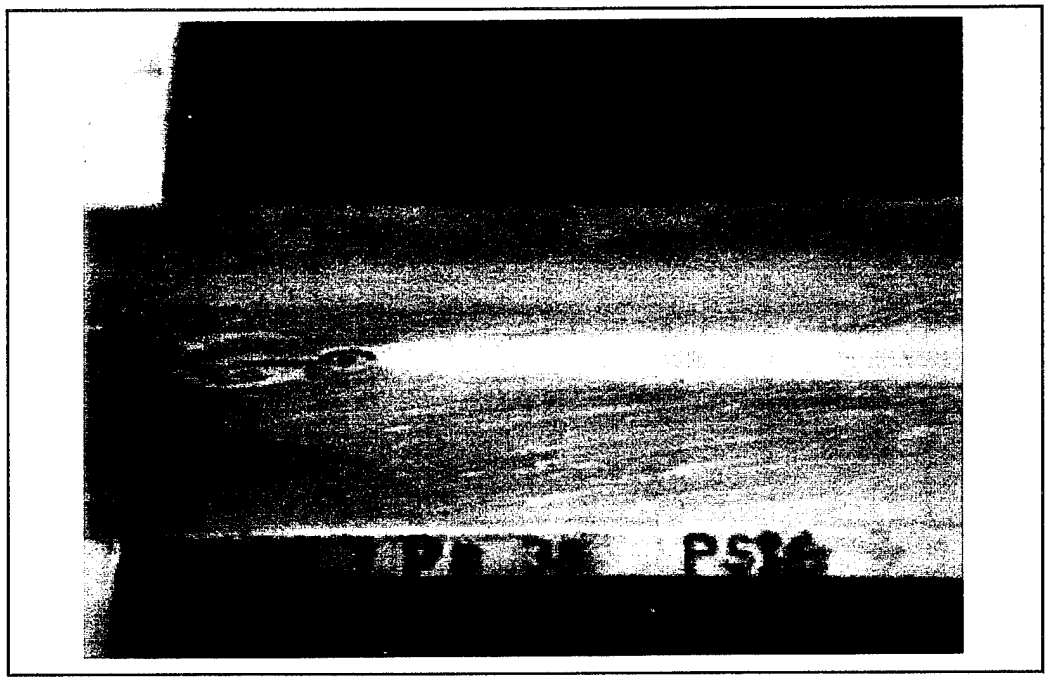


Figure 17b. Flow Visualization at 38 psig -- Acute View

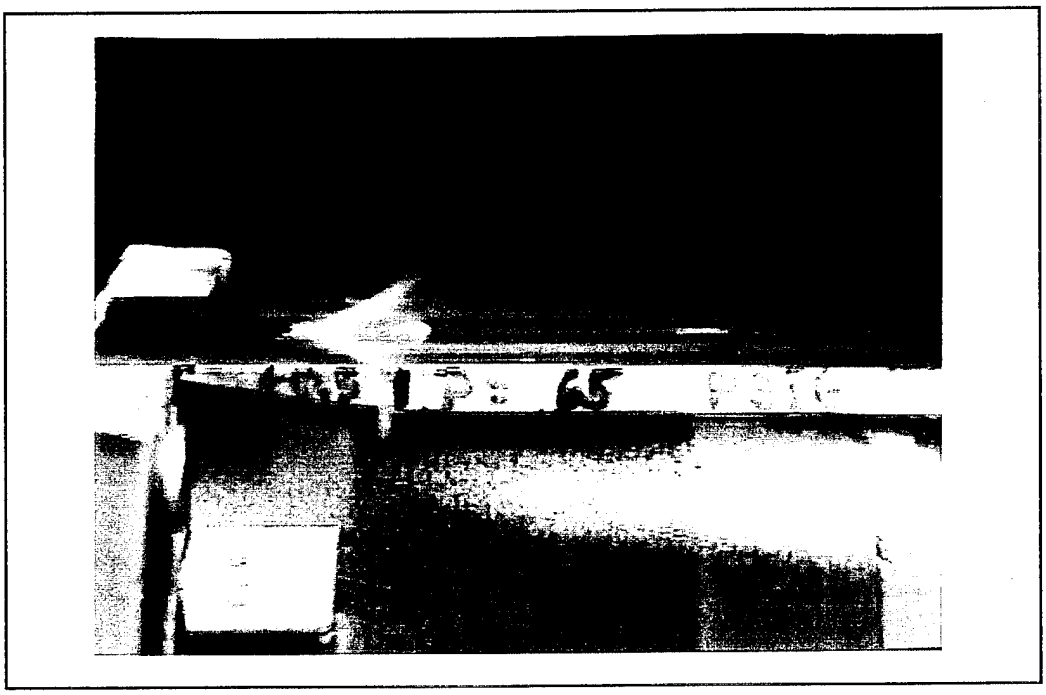


Figure 18a. Flow Visualization at 65 psig -- Cross Flow View

Figure 18b. Flow Visualization at 65 psig -- Acute View

portion of the injected mass would be expected to stagnate near the separation point, as the flow re-circulated within the bubble's boundaries. This is more clearly shown in the schematic of Figure 19. With increasing plenum pressure, the separation and recirculation region of the flow field gradually moved downstream, eventually encompassing the injection port, and allowing the alcohol to more clearly define the boundary of what was indicated to be a separation bubble.

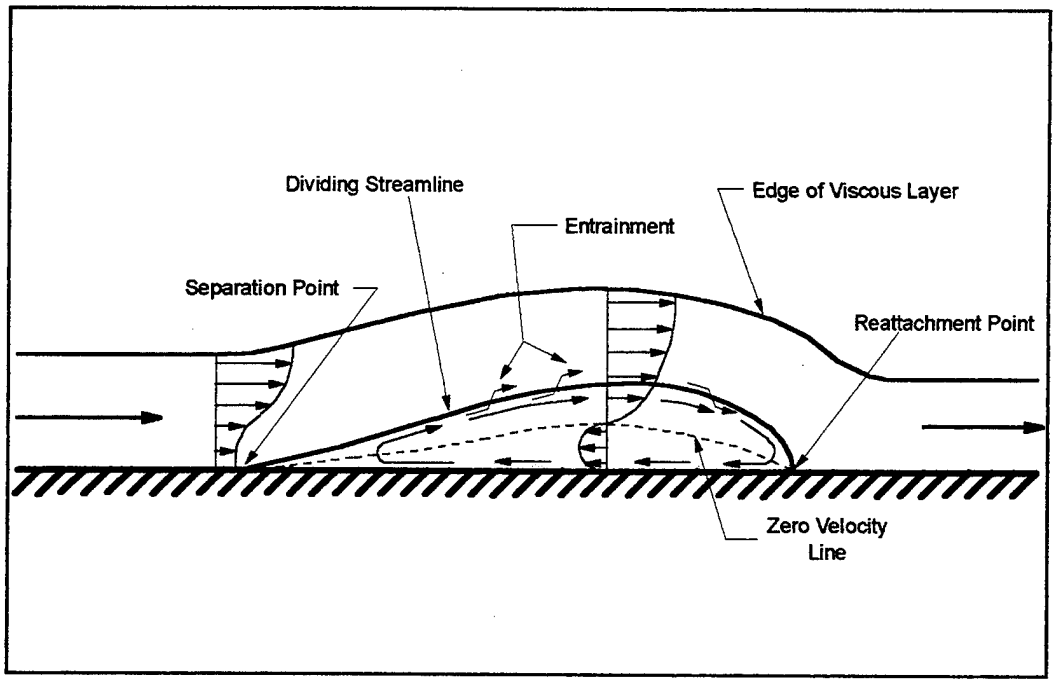


Figure 19. Details of Separation Bubble

To verify whether flow reattachment was in fact occurring downstream, a second injection port, port number 5, was rigged to concurrently admit methanol into the flow. Figures 20 through 23 show the sequence of images recorded in one such test.

Figure 20 shows that at 25 psig, attached flow was prevalent. At 40 psig, in Figure 21, the injectant at the first port (port number 2) indicated the presence of reversed

flow, while the injectant at the second port (port number 5) continued to indicate attached flow. The vortex patterns are an indication of the pressure gradients that exist within the bubble. In Figure 22, with the plenum pressure at 68 psig, the first sign of reversed flow is evident at the second injection port, while Figure 23 shows the port fully immersed in reversed flow at 75 psig.

The orientation of the plate relative to the centerline of the nozzle exit, and thus the centerline of the flow, was found to be 89.7 degrees. Since alignment could significantly influence the flow characteristics, the plate's inclination was changed to 90.3 degrees and the test runs were repeated. No dissimilarities between the results obtained at corresponding plenum pressures were noted.

The evidence of reversed flow and reattachment strongly suggested the presence of a closed separation bubble within the underexpanded jet when the plate was present. The apparent extent of the bubble, reaching 3/8 to 1/2 inch above the plate, is very surprising. However, it is consistent with the oblique shock in place of the normal shock. Further data are needed, such as impact probe measurements, in order to fully define the flow structure. For the present purpose, which was the investigation of pressure sensitive paint, this was not needed.

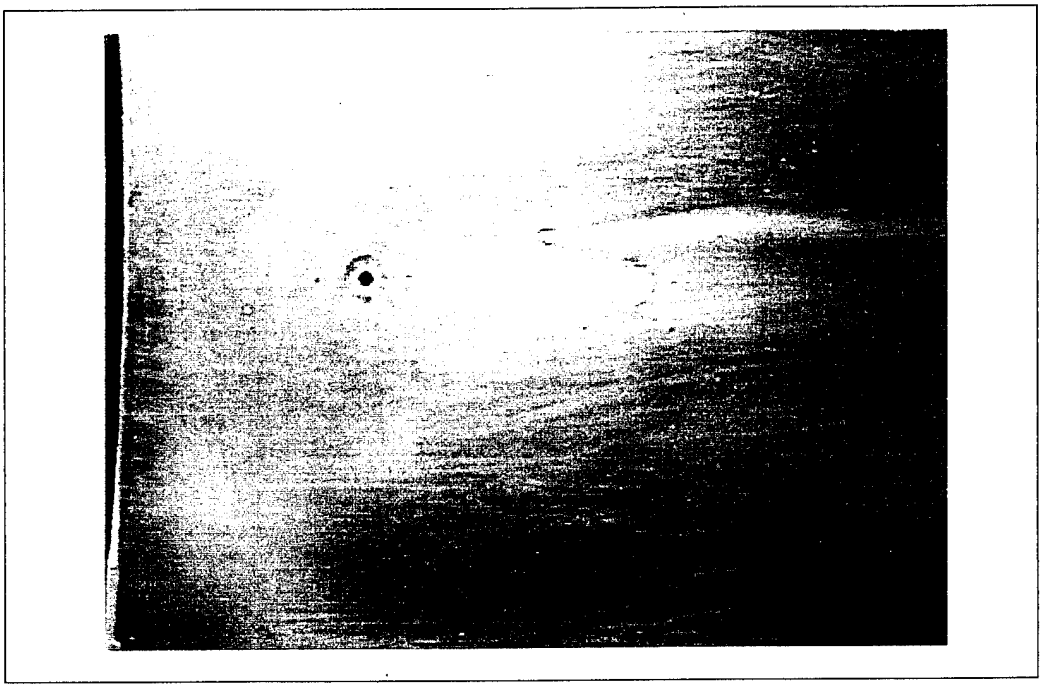


Figure 20. Flow Visualization at 25 psig

Figure 21. Flow Visualization at 40 psig

Figure 22. Flow Visualization at 68 psig

Figure 23. Flow Visualization at 75 psig

B. OPTICAL MEASUREMENT SYSTEM

The measurement system was composed of three main components: (1) the luminescence coating, (2) the illumination source, and (3) the luminescence detector and associated data processing hardware and software. Each component is discussed individually below. A schematic of the system used in conjunction with the free jet apparatus is illustrated in Figure 24.

1. Luminescence Coating

The luminescence coating used in the present work was developed by the Chemistry Department at the University of Washington and was provided, as a sample, by the NASA-Ames Research Center.

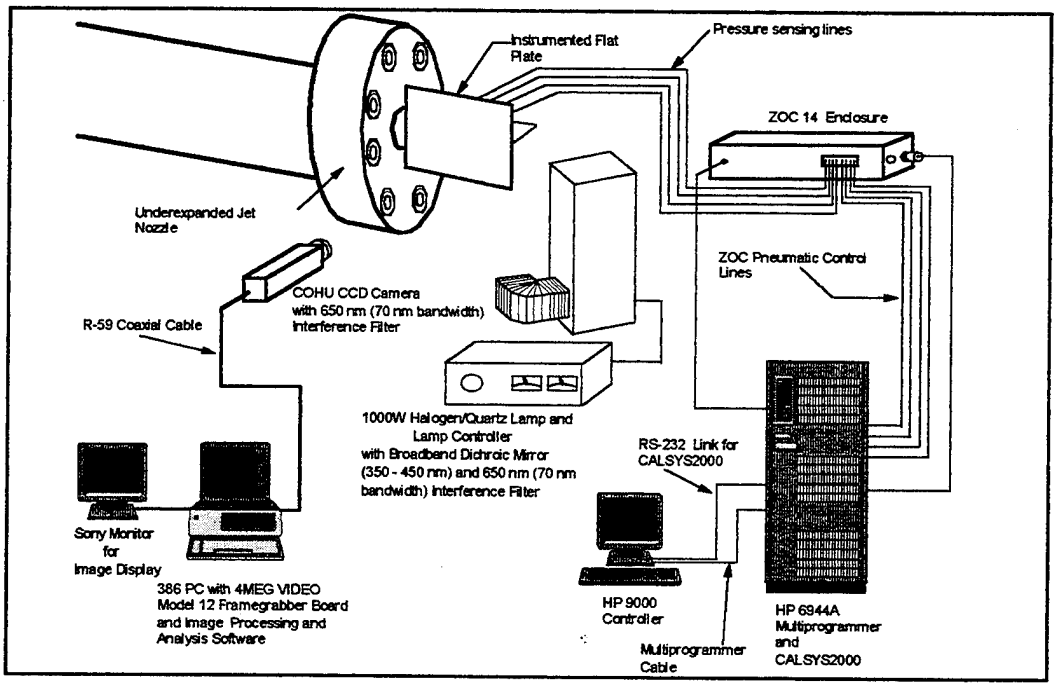


Figure 24. Schematic of Pressure Measurement System

The coating contained platinum octaethylporphyrin (PtOEP) as its active molecule. PtOEP has characteristics of high luminescent quantum yield (~90%), short triplet life (~100 micro seconds), and a high sensitivity to oxygen quenching [Ref. 1: p.35]. Figure 25 shows the excitation and emission spectra for the molecule. Excitation (absorption) peaks at 380 or 530 nm, whereas luminescence peaks at 650 nm.

The coating mixture consisted of the active molecule dispersed in a Genessee GP-197 polymer-resin solution. The concentration was 0.1 gm of PtOEP per liter of polymer resin [Ref. 19]. When the mixture was applied to the surface, the solvent evaporated leaving a hard, thin film of PtOEP dissolved in an oxygen-permeable polymer [Ref. 9: p. 35]. Several undesirable characteristics associated with this coating are described in Appendix B.

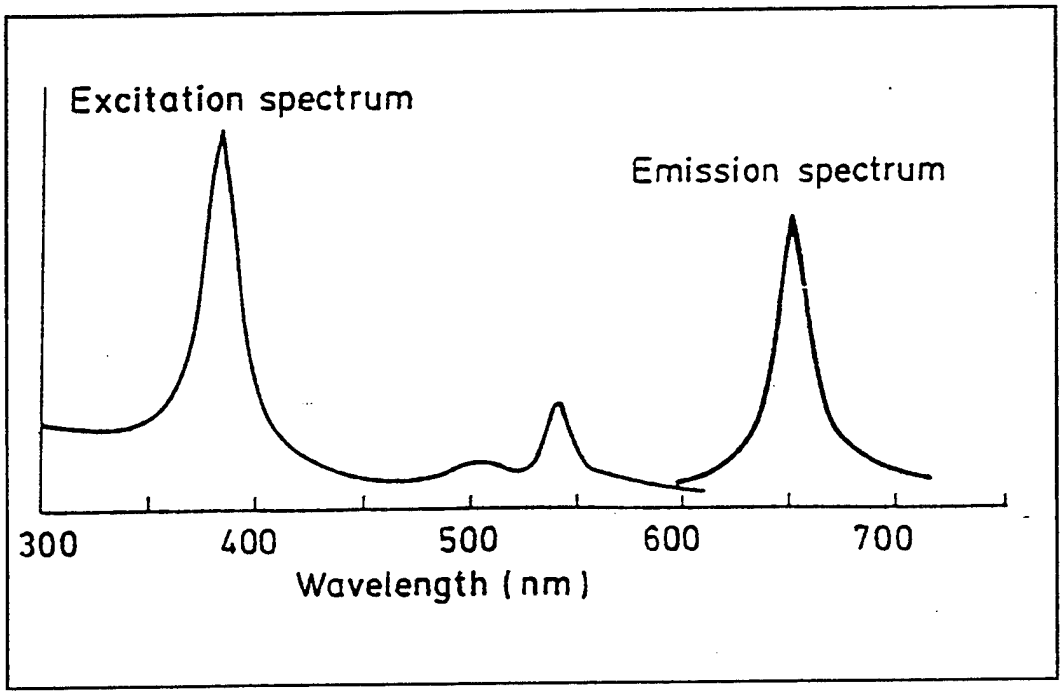


Figure 25. Excitation and Emission of Platinum Octaethylporphyrin

a. Reflective Backing

Before applying the luminescent coating to the surface, a white backing was first applied. A significant improvement in luminescence performance was thereby gained [Ref. 9: p. 32], allowing the camera to see a larger signal and an enhanced signal to noise ratio.

The particular type of white paint used for this backing was an important consideration. Kavandi [Ref. 9: p. 33] found that some paints tend to darken after long exposure to air and ultraviolet light. Krylon glossy-white spray paint (#1501) reportedly offered the greatest resistance to this effect and was therefore used in the current work.

2. Illumination Source

McDonnell-Douglas [Ref. 6: p. 3] considered several types of illumination sources to provide an adequate number of photons within the appropriate excitation wavelength of the paint. The results showed that tungsten-halogen incandescent sources were the most suitable in terms of compatibility and performance. Although the data in Figure 25 would suggest that arc lamps emit more energy in the excitation range of the coating, they also emit an EMF pulse that is damaging to CCD arrays. In addition, tungsten-halogen lamps are extremely stable, with minimum intensity fluctuations, and any such variations will directly effect the accuracy of the results. Consequently, an Oriel Corporation 1000 W quartz tungsten-halogen lamp, Model 66200, and the associated controller, Model 6405, were selected for the present measurement system.

Spatially-uniform illumination was also essential to reduce measurement errors. (According to McDonnell-Douglas [Ref. 6: p. 4], this is especially true when the surfaces are highly curved). Non-uniformity was found when the published procedures [Ref. 20: p.13] were followed to produce a collimated beam from the light source. The procedure resulted in generating a focused image of the filament in the lamp. However, by reversing the orientation of the barrel containing the lenses, a greater range of adjustment was achieved. Figure 26 illustrates this modification, which made it possible to produce a more uniform beam, although a slight degradation in spectral intensity was noted.

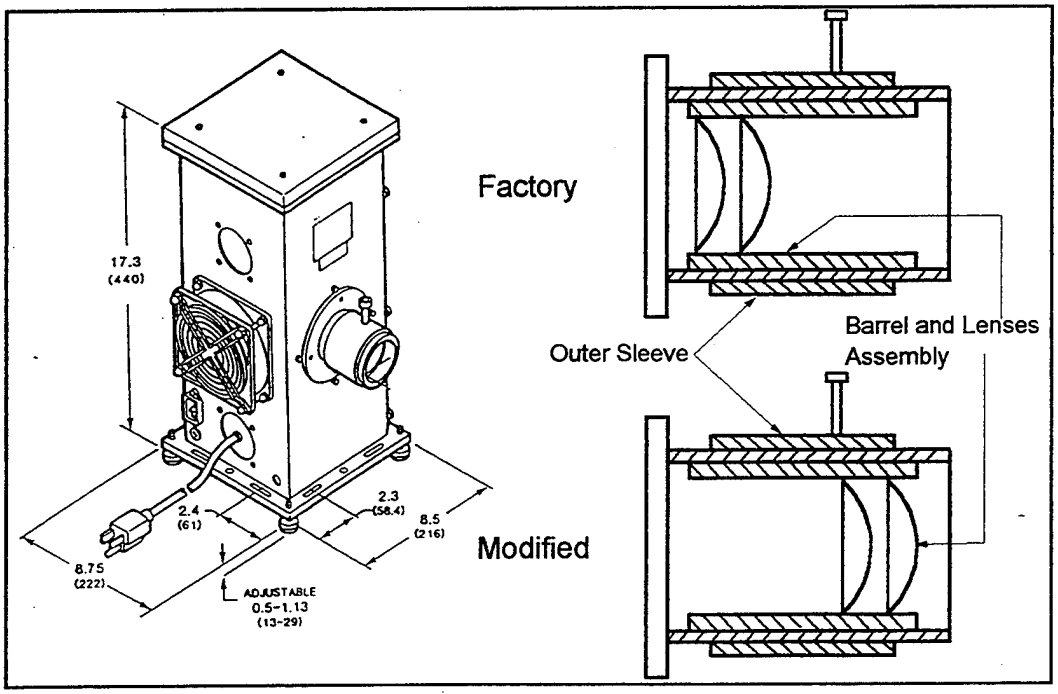


Figure 26. Modification of Focusing Assembly of the Light Source

a. Filters

The use of a broad-band light source mandated the use of filters to ensure that the appropriate wavelength for excitation of the luminescence was allowed to pass while blocking unwanted light. Unwanted light was that which would pass through the narrow-band filter that was installed on the camera.

As Figure 25 shows, there are two wavelengths at which excitation of the luminescent paint is optimum. Although either wavelength could have been used, the 380 nm wavelength was chosen because of its greater separation from the emission wavelength of 650 nm. This also had the advantage, as discussed in [Ref. 6: p. 5], of allowing a filter with a more gradual cutoff to be used which would allow more light energy to be utilized to excite the paint.

A combination of filters was used in the illumination system to isolate the 380 nm wavelength. The source beam first passed through a dichoric or cold mirror, Oriel Model 66228, which had a spectral range of 350 - 450 nm and a cut-off frequency of 550 nm [Cold mirrors are oriented at 45 degrees relative to the incoming beam from a source. The infrared wavelengths are transmitted undeviated, while the ultraviolet wavelengths are reflected through 90 degrees. This prevents the infrared from being reflected back to the source and overheating the system.]

The source light was then directed through an Oriel interference filter, Model 57521, having a bandwidth of 70 nm centered at 400 nm. The filters were installed in a 90

degree beam turner and mirror holder, Oriel Model 66246, which was fitted to the lamp housing.

Finally, the camera used to record the emitted luminescent energy from the paint had a 650 nm interference filter with a 70 nm bandwidth, Oriel Model 57610, mounted over its lens to block out all other frequencies.

3. Detection System

Luminescent data were acquired using a COHU Model 4910 high performance, monochrome, low-intensity CCD camera and transferred to a framegrabber board in a 80386 PC using an R-59 coaxial cable. The camera was fitted with a Cosmicar 16 mm, f/1.4 lens. To ensure the output signal would be linearly proportional to light intensity received, the camera was configured with the gamma set equal to one and the automatic gain control (AGC) disabled [Ref. 2: p. 3342]. The camera's spectral response, as shown in Figure 27, shows that its relative response at 650 nm is approximately 65%.

The camera produced a frame every 1/30 of a second and thus was limited to recording pressure fluctuations at rates less than 30 Hz. [A simple test to determine if the illumination system was bleeding over into the detection system was to illuminate an unpainted surface (i.e., no luminescent paint) and then direct the camera towards this surface to see if any spurious light was being detected. None should be present].

The analog output signal from the camera was initially digitized using an IDEC Supervision 16 framegrabber board residing in a 80386-based PC. The raw data were then reduced and analyzed using "Image Pro Plus" analysis and processing software.

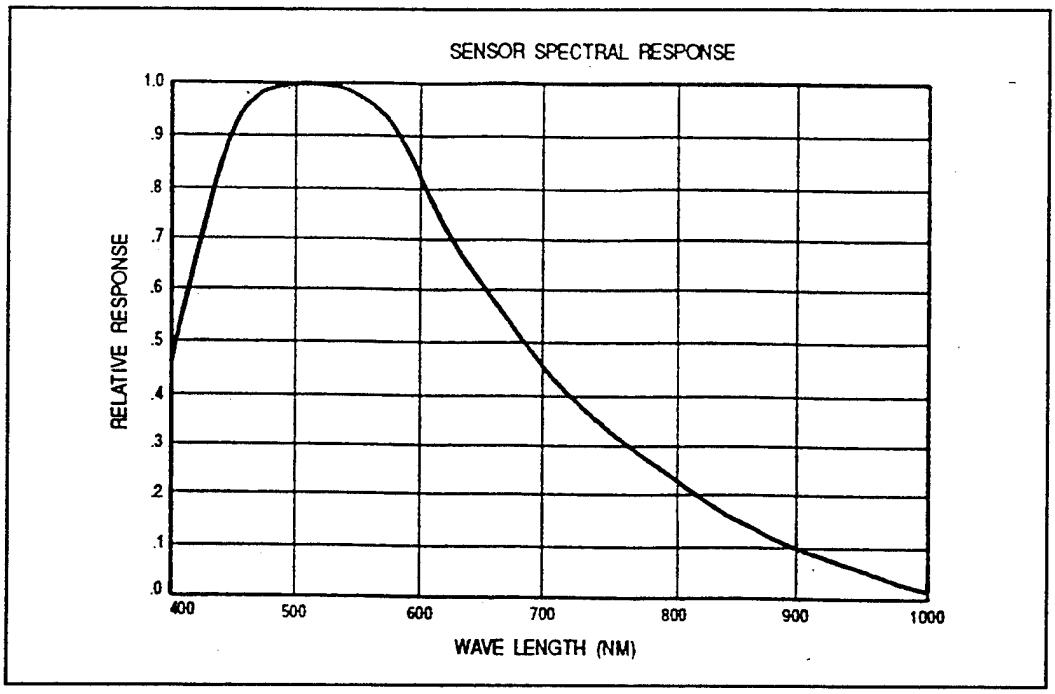


Figure 27. Spectral Response Curve for the COHU Camera Model 4910

However, this hardware/software combination was extremely limited in application resulting in long data acquisition periods and time-consuming data reduction. Because of the characteristic degradation of the luminescent coating, the accuracy of the data was questionable.

The initial hardware/software combination was replaced with a much more versatile Epix 4MEG Video Model 12 framegrabber board and software which included image analysis and processing programs. The spatial resolution of the framegrabber was operator adjustable, thus a balance between sampling resolution and the board's memory storage could be tailored to a given application. For the underexpanded-jet and flat-plate work, the spatial resolution was set to 752 x 480, the highest resolution setting. The gray-level resolution of the board was 8-bits.

C. EXPERIMENTAL PROGRAM

1. Flat Plate Preparation

The surface of the flat plate was cleaned with acetone, ensuring the removal of all oils and dirt. Fine wire was then inserted into each of the pressure ports to prevent paint from entering the holes. The white Krylon undercoating was then applied in a series of three to four thin coats, allowing four to five minutes between coats. Ten minutes after applying the last coat, the fine wires were removed from the ports. This was necessary to prevent the paint from drying on the wire. [Significant portions of the undercoating could be removed from around the pressure port when extracting a wire to which the paint had hardened]. At this point, the white undercoating was allowed to dry for one hour.

Prior to the application of the pressure-sensitive paint, the fine wires were re-inserted into the ports. The luminescent coating was then applied to the surface using a standard hobby airbrush. The nitrogen supply in the Gas Dynamics Laboratory was used as the pressure source for the airbrush (instead of shop air) as it offered a contaminant-free pressure source. With a properly adjusted airbrush and a good painting technique, continuous application of the luminescent coating to the surface could be achieved until the surface was "suitably" covered. Although Kavandi *et al* [Ref. 2:p. 3343] refers to normal coating thickness as being in the range of 5 to 15 micrometers, it was both impractical and unnecessary to measure the coatings to determine if the paint fell within these prescribed limits. The approach used in the present work was simply to observe when the pigment of the pressure-sensitive paint seemed insensitive to further application,

and that the texture of the surface appeared smooth. Several attempts were necessary to develop the technique and the judgement in applying the luminescent coating. Three to four minutes after the completion of the coating, the fine wire were removed. Once the model was installed for testing, sufficient time had elapsed for the coating to have properly cured. Note that it was important to avoid touching the painted surface at any time since body oils could adversely affect the behavior of the luminescent coating.

2. Experimental Procedure

Setting the video resolution for the framegrabber to the maximum (752 x 480) resulted in 11 frame buffers being available to store for image data. The controlling software for the framegrabber was capable of capturing a sequence of images, digitizing them, and storing each image of the sequence in consecutive image buffers, the number of buffers used in the sequence (from one up to the number of available buffers) being specified by the operator. Because of the limitation of collecting only 11 images for each execution of the sequence algorithm, and the fact that averaging one hundred images was desirable to obtain noise-free data, for each of the wind-on and wind-off conditions, ten runs were executed. (10 frame buffers vice 11 buffers were utilized). Since the underexpanded free jet was a steady and repeatable event, this method of collecting data was a feasible solution for the limited memory of the frame-grabber board.

The data for the wind-off condition was collected first. The flat plate was illuminated with the tungsten-halogen light source while the laboratory lights were turned off, preventing any spurious wavelengths from entering the camera and offsetting the

image data. A real-time image of the plate was displayed on the image monitor so that the camera output could be adjusted for the best quality picture using a combination of focus, manual gain, and lens iris. Manual gain was necessary because of the low light condition, but care had to be exercised because with an increase in gain there was an accompanying increase of noise introduced into the image. The shutter speed for the camera was set to off.

After the first sequence of images was captured and stored in the frame buffers, the light source was switched off to minimize the degradation to the paint. The light source was such that the line voltage applied to the lamp housing was adjustable; however, power was ultimately controlled with an on/off switch. Thus, the same illumination intensity was maintained each time the lamp was turned on.

The ten images were averaged together to form a single image. The single image was saved to a floppy disk. The light source was again switched on in preparation for the second sequence of images, allowing time for the luminescent coating to reach its maximum intensity. (This is referred to as the "induction period", which is explained in Appendix B). The second sequence of images was then captured and stored, and the tungsten-halogen lamp shut-off. The images were averaged to give a single image and again saved to floppy disk. This routine was executed until ten averaged images for the wind-off condition had been saved to floppy disk. Each sequence of capturing the data took less than one minute.

The procedure for obtaining images for the wind-on condition was similar. With the light source on and the plate properly illuminated, the underexpanded-jet apparatus was started. Once the desired pressure was set using the plenum control valve, and the pressure was stabilized, the imaging sequence was executed. When the software had completed its routine, the jet was shutdown and the light source turned off. The jet apparatus was equipped with a shutoff valve so that the jet could simply be turned on and off without disturbing the setting of the plenum control valve. This ensured repeatability of the event for each sequence of 10 images.

It is important to note that throughout these events, the camera and light source had to remain fixed, spatially, with respect to the plate. In addition, no adjustments of any kind could be made to the instruments or equipment. Any deviations would introduce errors into the results.

Conventional pressure data were obtained concurrently with the luminescent paint data using the CALSYS2000 data acquisition system [Ref. 17]. Twenty samples per port using a data collection rate of 33 Hz were obtained and averaged together. These pressure data would be used later in the calibration process. Ambient pressure and temperature were also recorded.

3. Image Data Reduction

a. Image Processing

Several image-processing techniques were used to manipulate the data in order to obtain the desired result. The techniques are described individually below.

Appendix C provides a summary of the steps used in operating the EPIX software for acquiring, processing, analyzing, and reducing the data.

Round-off error from the image processing routines was a concern. To ensure against loss of accuracy due to round-off error, the system hardware had to be capable of doing at least 16 bit arithmetic. The EPIX frame grabber board was capable of conducting 32-bit operations. When the image was processed, the 8-bit intensity values for each pixel in the image were first converted to 32 bit words. Once the processing was complete, the modified values of each pixel were converted back to an 8-bit format for display. If the mathematical operations were conducted with anything less than 16-bit precision, all significant digits would be truncated.

(1) Averaging. The emission of photons from any source is a random process following a Poisson distribution, and the number of photogenerated carries collected in a potential well of the camera array (see Appendix D for an explanation on the operation of a CCD camera) in time "t" is thus a random variable. The standard deviation of this random variable is referred to as photon (shot) noise. This noise is a fundamental limitation in all imaging applications since it is a property of light itself, not of the image sensor.

By averaging a sequence of images, the signal-to-noise ratio of the data has been found to be significantly improved. This process has the effect of reducing the scatter in the luminous intensity measurement [Ref. 6:p. 8]. McDonnell-Douglas [Ref. 6]

has found that as few as eight images averaged together showed a marked reduction of noise on the signal.

The reason for choosing one hundred images for each of the wind-on and wind-off conditions was the prior experience in the work conducted by NASA-Ames, the University of Washington, and McDonnell-Douglas. In each case, one hundred images was adopted in all work done to date.

The ten averaged images of the wind-off condition were loaded into ten frame buffers of the EPIX framegrabber board. As with the initial averaging of the raw image data, the ten buffers were averaged together to form a single image. This single image, a result of averaging one hundred "raw" images together, was then saved to floppy disk. The corresponding wind-on images were averaged in a similar manner, and the resultant image saved with its wind-off counterpart.

The procedure used in averaging the data in the present work was slightly different than used at NASA-Ames, the University of Washington, and McDonnell-Douglas. In those cases, one hundred images were collected and then averaged in one step. In the present work, ten averaged images were averaged to form the final image. Again, this is a result of the limited memory available on the frame grabber board. However, since each image has a random distribution of data associated with it, the averaging technique used will have little effect on the outcome of the result.

The significance of image averaging can be seen in Figures 28 through 30. In each figure, an image and a graphical distribution along a single line of pixel values in

the image is shown. Figure 28 shows a single raw image of the wind-on condition at 80 psig. Figure 29 shows the effect of averaging ten wind-on images together and Figure 30 shows one hundred images averaged together. In each figure, an image and a graphical distribution along a single line of pixel values in the image are shown.

(2) Dark Current. Appendix D details what dark current is and how it affects the storage of photogenerated carriers in the potential well of a photo-sensitive array element. The effect of the dark current on an image is that it produces an offset in which the zero incident light condition does not correspond to the zero grey level. To correct for this offset, a "dark" image was acquired and then subtracted from the wind-off and wind-on conditions.

To acquire a dark image, a lens cover was placed on the lens prohibiting any light from striking the CCD array, and then an image was acquired. One hundred images were taken and averaged as was done with the wind-on and wind-off conditions. A dark image was generated after each of the wind-on runs. Analysis of the dark current image showed that 1 to 2 grey levels were present, which were the levels subsequently subtracted from the wind-off and wind-on images.

(3) Registration. When a pixel-to-pixel comparison of two images of the same object field taken from the same sensor at different times is desired, it is necessary to spatially register the images to correct for relative translational shifts, rotational shifts, and geometrical distortions. In the general case, this is accomplished in the software

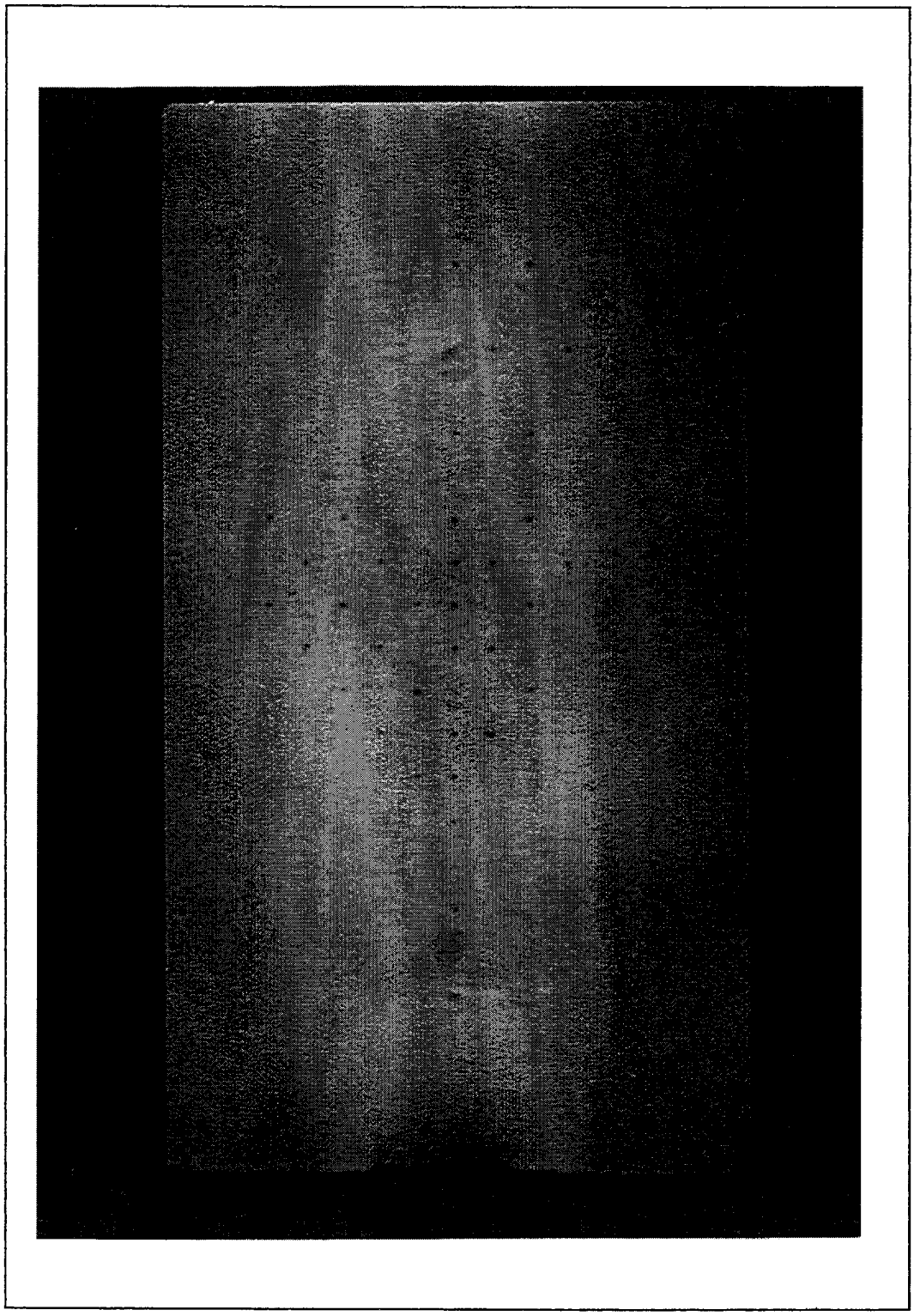


Figure 28a. Single Image of the Underexpanded Jet Across the Flat Plate at 80 psig

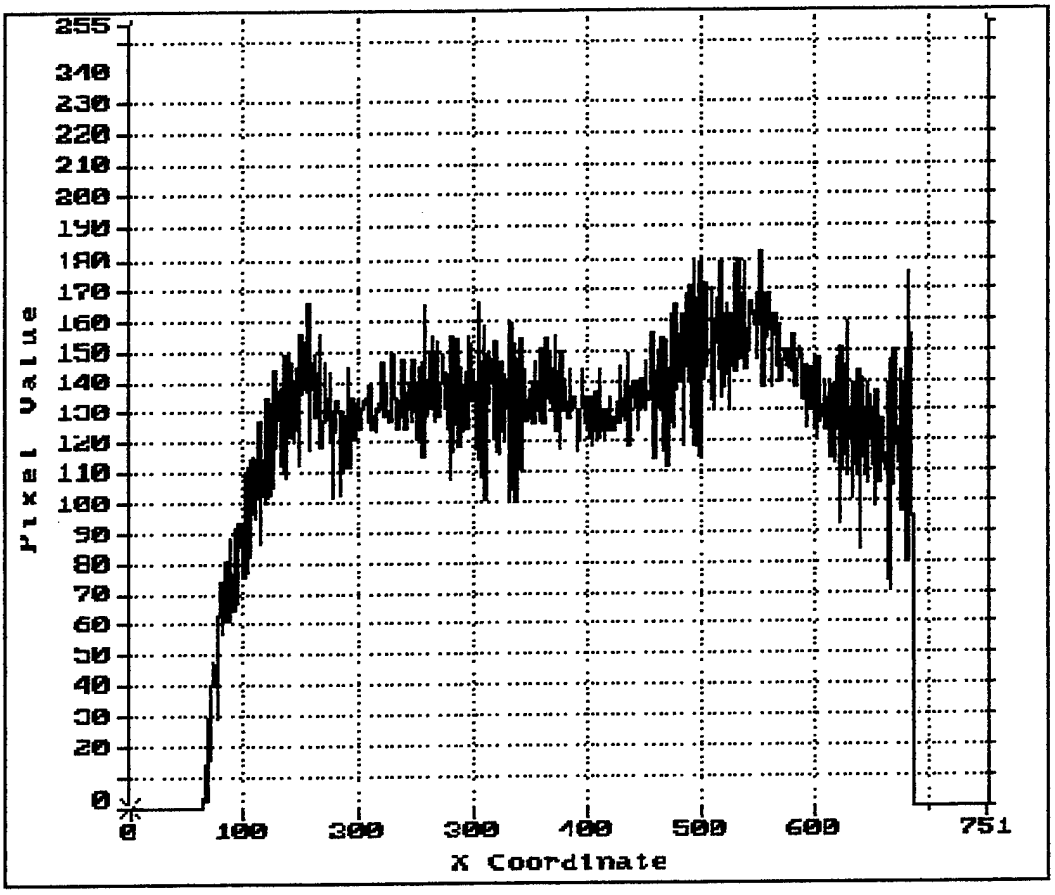


Figure 28b. Graphical Representation of a Single Line of Pixels of a Single Image

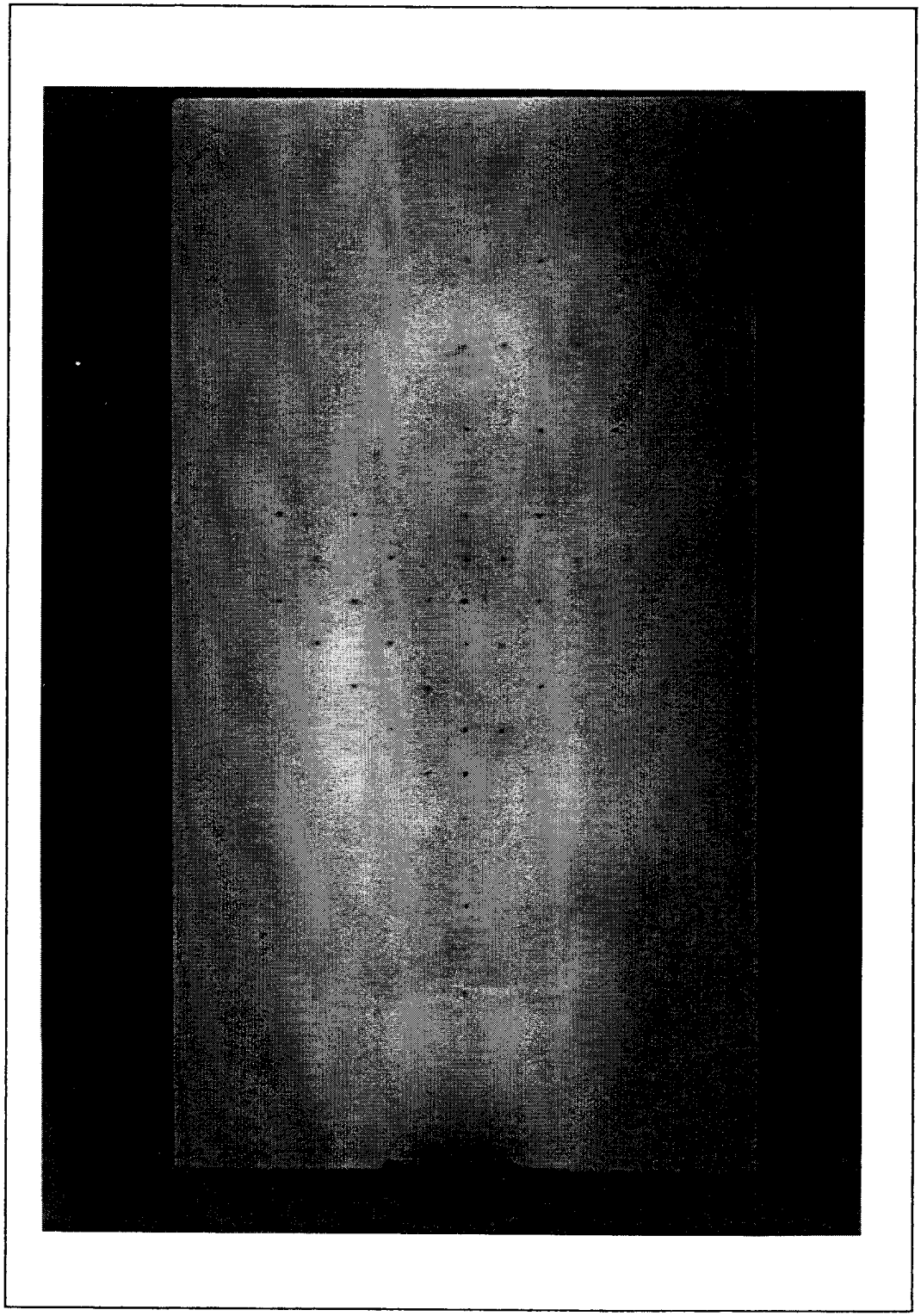


Figure 29a. Ten Averaged Images of the Underexpanded Jet Across the Flat Plate

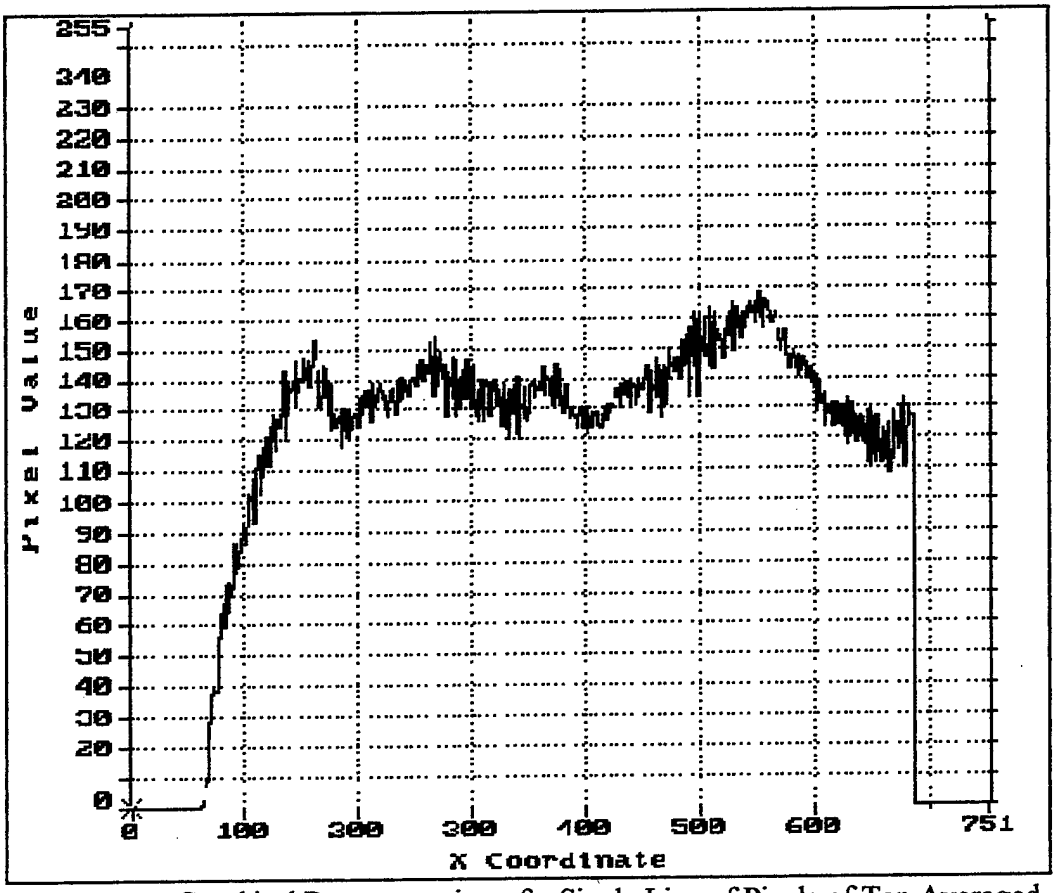


Figure 29b. Graphical Representation of a Single Line of Pixels of Ten Averaged Images

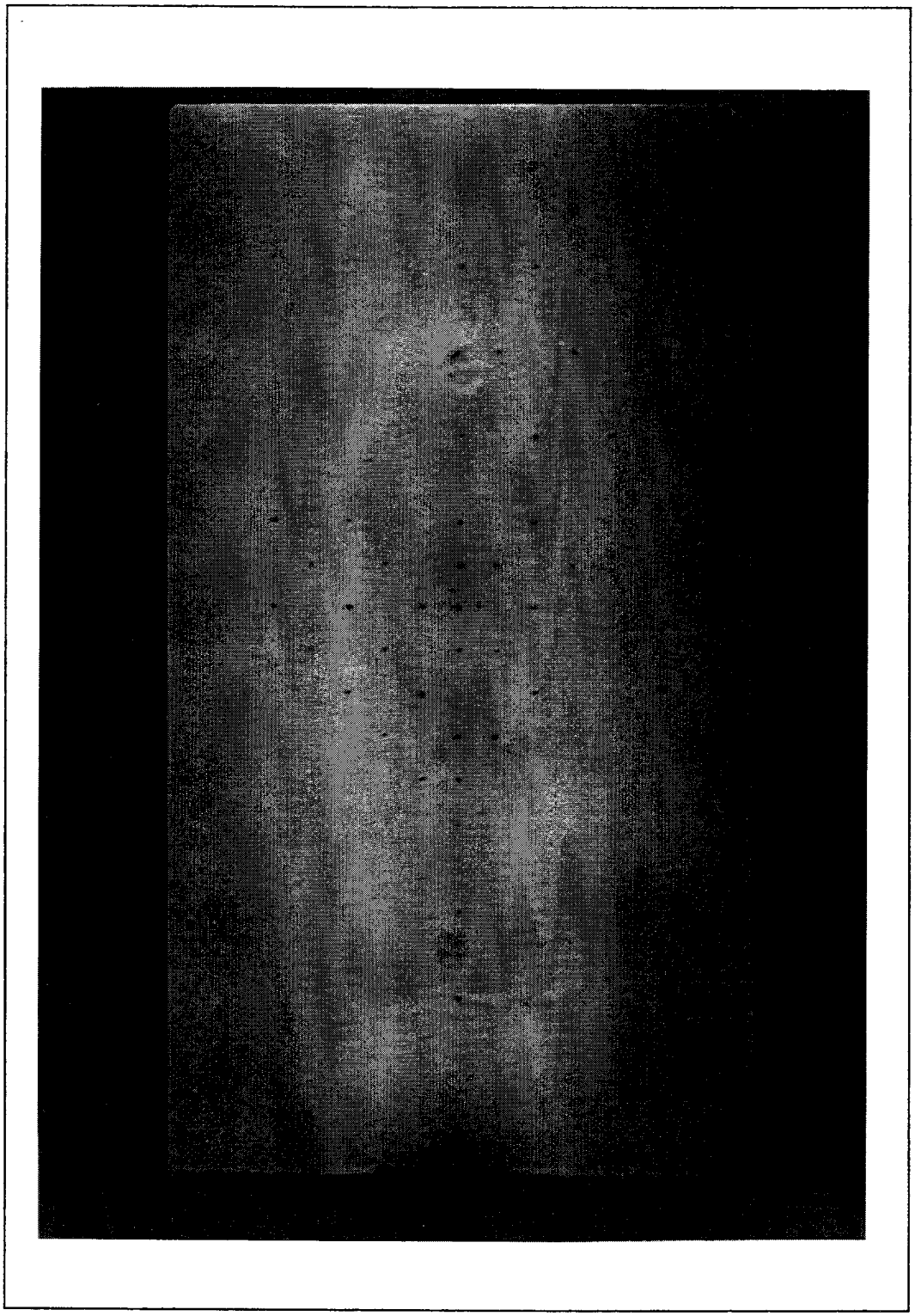


Figure 30a. One Hundred Averaged Images of the Underexpanded Jet /Flat Plate

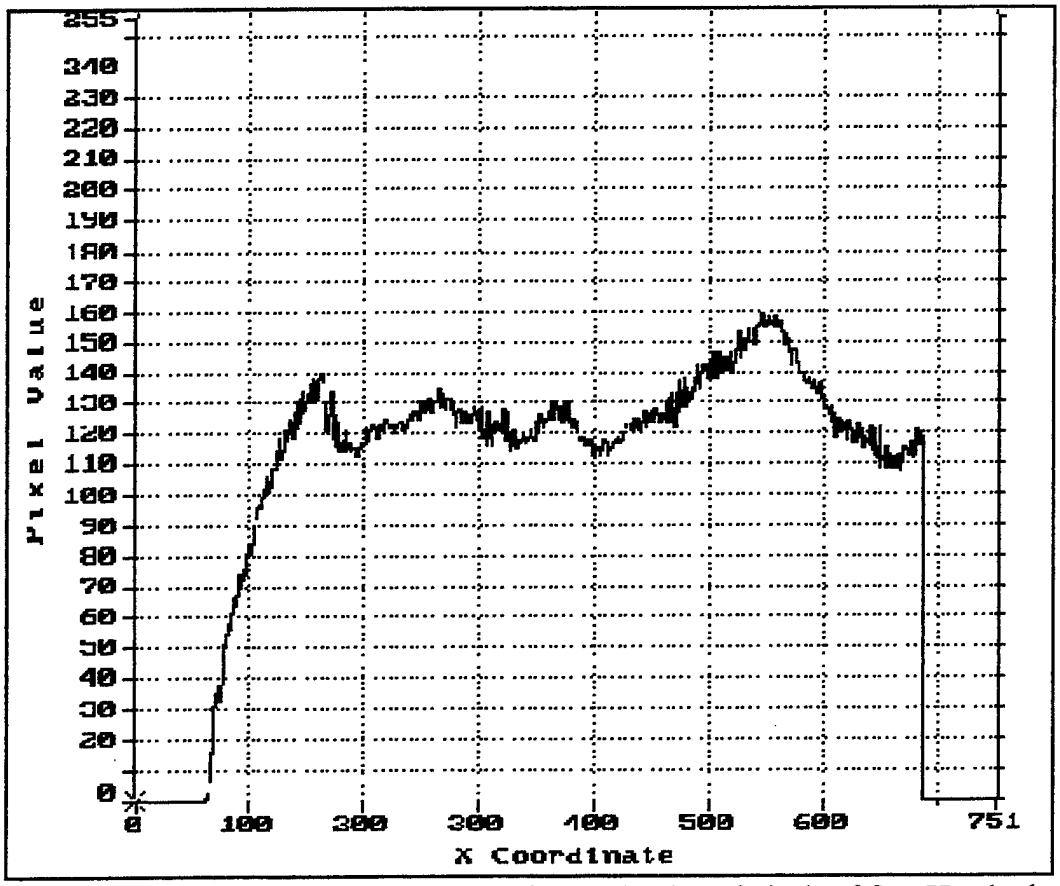


Figure 30b. Graphical Representation of a Single Line of Pixels of One Hundred Averaged images

using a pair of transformation equations relating the new coordinates to the old coordinates. An example set of transformation equations, termed the *affine projection*, are

$$x' = (a_{11}x + a_{12}y + a_{13})/(a_{31}x + a_{32}y + 1)$$

and

$$y' = (a_{21}x + a_{22}y + a_{23})/(a_{21}x + a_{32}y + 1)$$

where x,y are the old coordinates and x',y' are the new coordinates. The eight unknown coefficients in the two equations can be determined if the coordinates of four points, called control points, can be determined from each of the two images involved. [Ref. 21:p. 71]

In the jet/plate interaction experiment, the stiffness of the plate was expected to be sufficient to withstand the forces imposed on it by the jet so that any deformation that did occur would be insignificant, making registration unnecessary. However, comparison of the wind-on and wind-off images showed that the plate did experience a horizontal translation when the jet was on. It was found that the thrust produced by the jet caused a deformation in the structure supporting for jet apparatus. Thus, the jet apparatus and flat plate in combination experienced a displacement relative to the camera.

Examination of the wind-off and the corresponding wind-on images showed that for the 65 and 80 psig cases , the images had shifted one pixel width in the direction of the thrust, and two pixel widths for the 90 psig case. The image-registration algorithm in the EPIX software was found to be unsuitable for this correction. In

addition, the lack of "natural" features on the plate to serve as control points did not allow the use of the software. [When the object lacks such features and image registration is anticipated, artificial marks such as black circles can be distributed on to the surface. In the present case, registration was not expected to be needed, the plate was not so equipped.]

The registration between the wind-off and wind-on images was a relatively simple issue involving rigid body motion in one dimension. For this particular situation the images were aligned using the "Copy and Shift Image" function in the EPIX software which allowed an image to be shifted in its buffer up or down, left or right by an operator- specified number of pixels. The registration scheme was accomplished by first loading the wind-on and wind-off images into consecutive image buffers. The wind-on condition was considered the "warped" image and the wind-off image the "reference" image to which the warped image would be registered. A cursor overlay was simultaneously displayed on the image monitor with the wind-off image. The cursor was adjusted so that its horizontal character overlaid the pressure ports along the centerline of the plate while the vertical character of the cursor overlaid the pressure ports along the vertical centerline of the plate. The cursor remained fixed relative to the screen of the monitor; this served as a reference for comparison of object feature location when shifting between the wind-on and wind-off buffers. The wind-on image was then shifted relative to the vertical-cursor character until the vertical centerline pressure ports were overlaid by the vertical cursor character. When complete, the images were considered registered.

The accuracy of using this approach was judged to be similar to that of registration software since the registration software normally requires the operator to manually locate the control points in each image. In addition, since the body moved relative to the light source, consideration must be given to whether changes in brightness were due to the pressure variations, or were caused by the motion of the plate. McClachlan *et al* [Ref. 22:p. 3] indicate that this is of greatest concern when model deflections and distortions are extreme. Since the flat plate motion consisted of rigid body translation, the magnitude of which was extremely small, this concern was considered to be insignificant.

(4) Ratioing. While the reason for ratioing the wind-off image with the wind-on image was to satisfy the Stern-Volmer relation and produce a pressure map, there were other benefits which arose from the procedure. In Figure 31 it is easy to discern the gross features of the pressure distribution in the wind-on image. The ratioing process had the affect of enhancing the finer detail in the image that would otherwise be too subtle for detection. [Ref. 7:p. 7]

Examination of the wind-off image in Figure 32 shows the evident brightness variations from point to point across the surface. This was due to a combination of differences in illumination, paint thickness variations, and features in the model itself. Figure 33 shows a three dimensional graphical representation of the wind-off intensity values across the surface of the plate. This illustrates the variations that exist across the plate. The result of ratioing was the elimination of these non-uniformities.

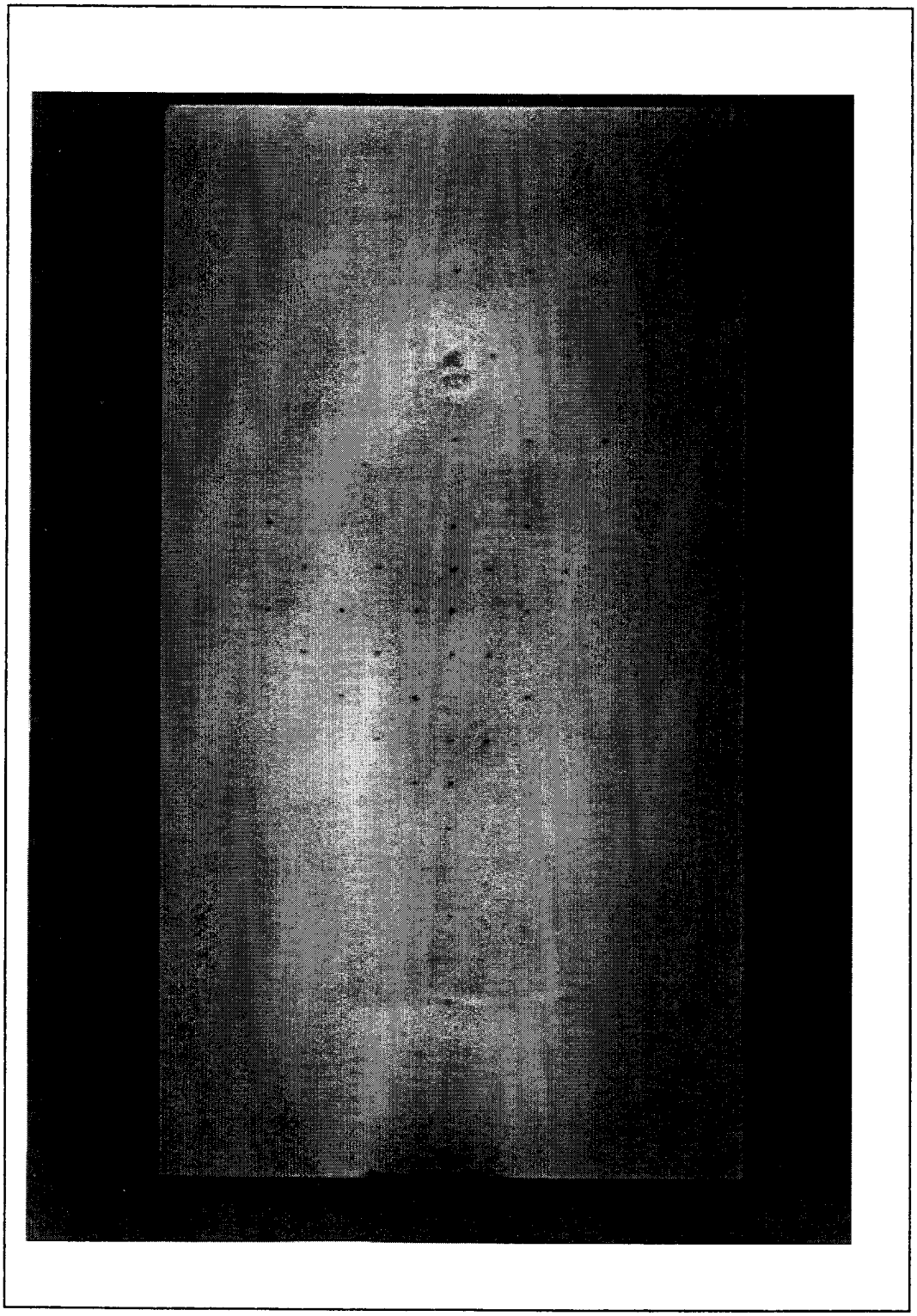


Figure 31. Wind-on Image of the Underexpanded Jet at 80 psig Across a Flat Plate

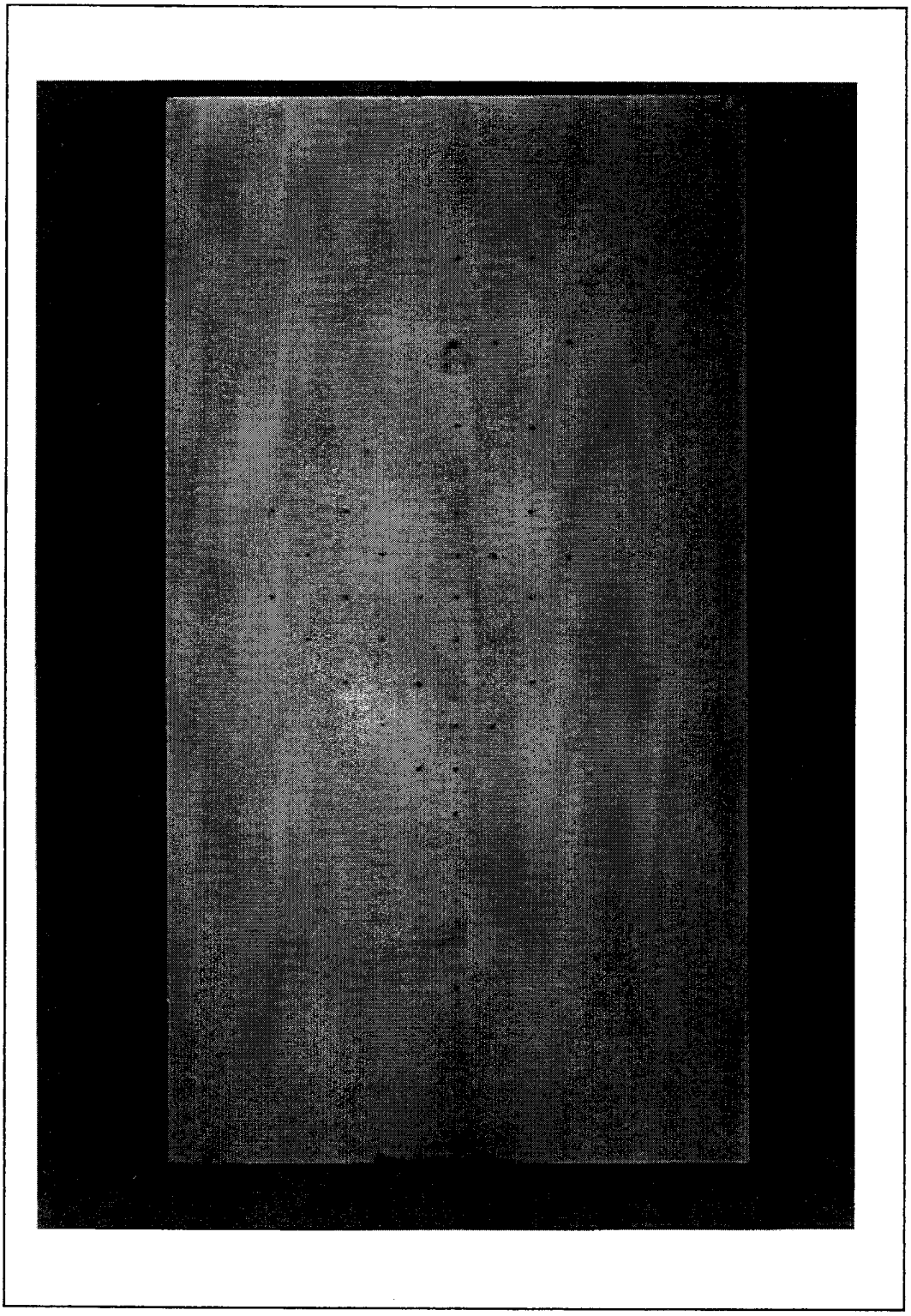


Figure 32. Wind-off Image for the 80 psig Condition

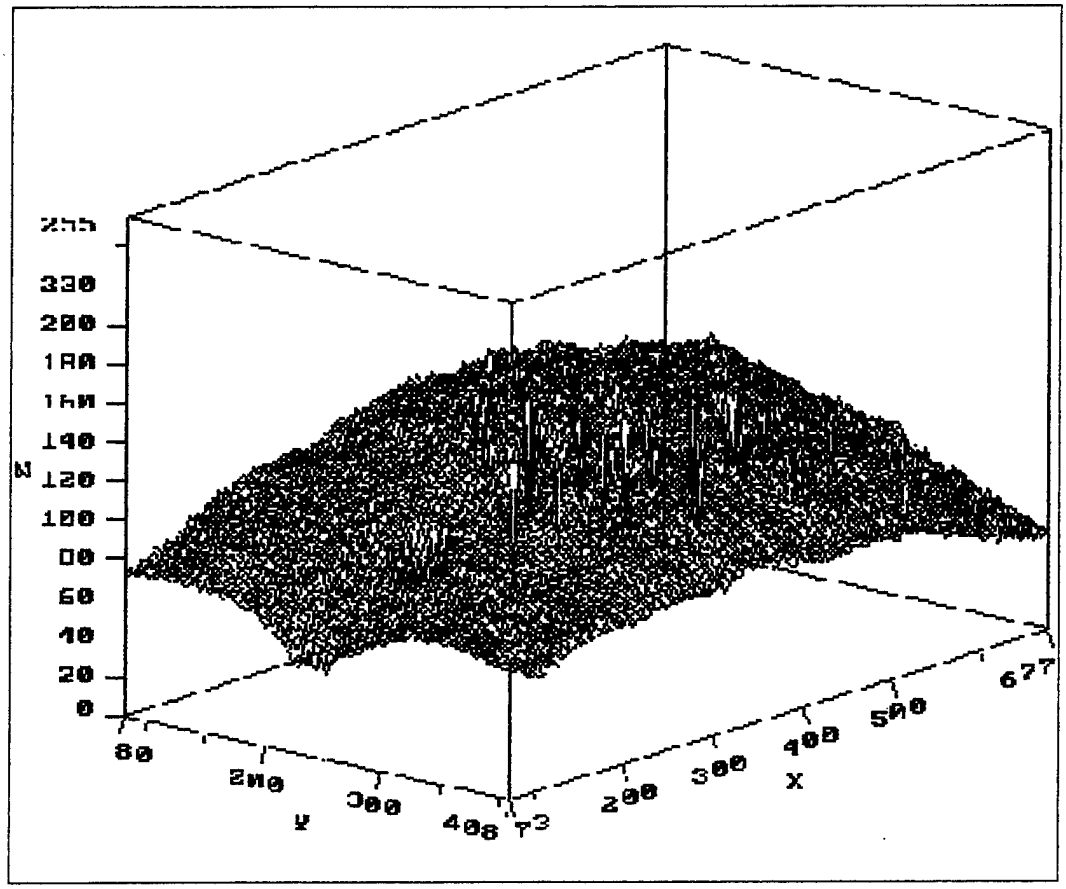


Figure 33. Three Dimensional Intensity Plot of the Wind-off Condition of the Plate

The "Ratio Image Operation" under the "Two Image Arithmetic" menu of the EPIX software formed the weighted ratio of corresponding pixels. The operation is mathematically expressed as

$$(c0 * PixB + c1)/(c2 * PixA + c3)$$

where the coefficients c0, c1, c2, and c3 are modifiable. For the current work, PixA was designated the wind-on image while PixB, the wind-off image. In addition, the coefficient c0 was assigned the value of 100 while the coefficients c1, c2, and c3 were assigned the values 0, 1, 0 respectively. The reason for assigning c0 the value of 100 was to scale the resultant ratioed intensity map such that differences of the grey values between neighboring pixels could be discerned.

Figure 34 illustrates the ratioed image for the underexpanded jet across the flat plate at 65 psig plenum pressure. The importance of proper registration of the wind-on and wind-of images prior to ratioing cannot be overstated. To illustrate the effect of improper registration, the images used to form the resultant image in Figure 34 were modified where the wind-on condition was shifted an additional five pixel widths in the direction of the thrust. The result of ratioing these two images is shown in Figure 35. A reduction in fine details, as compared to Figure 34, is clearly evident.

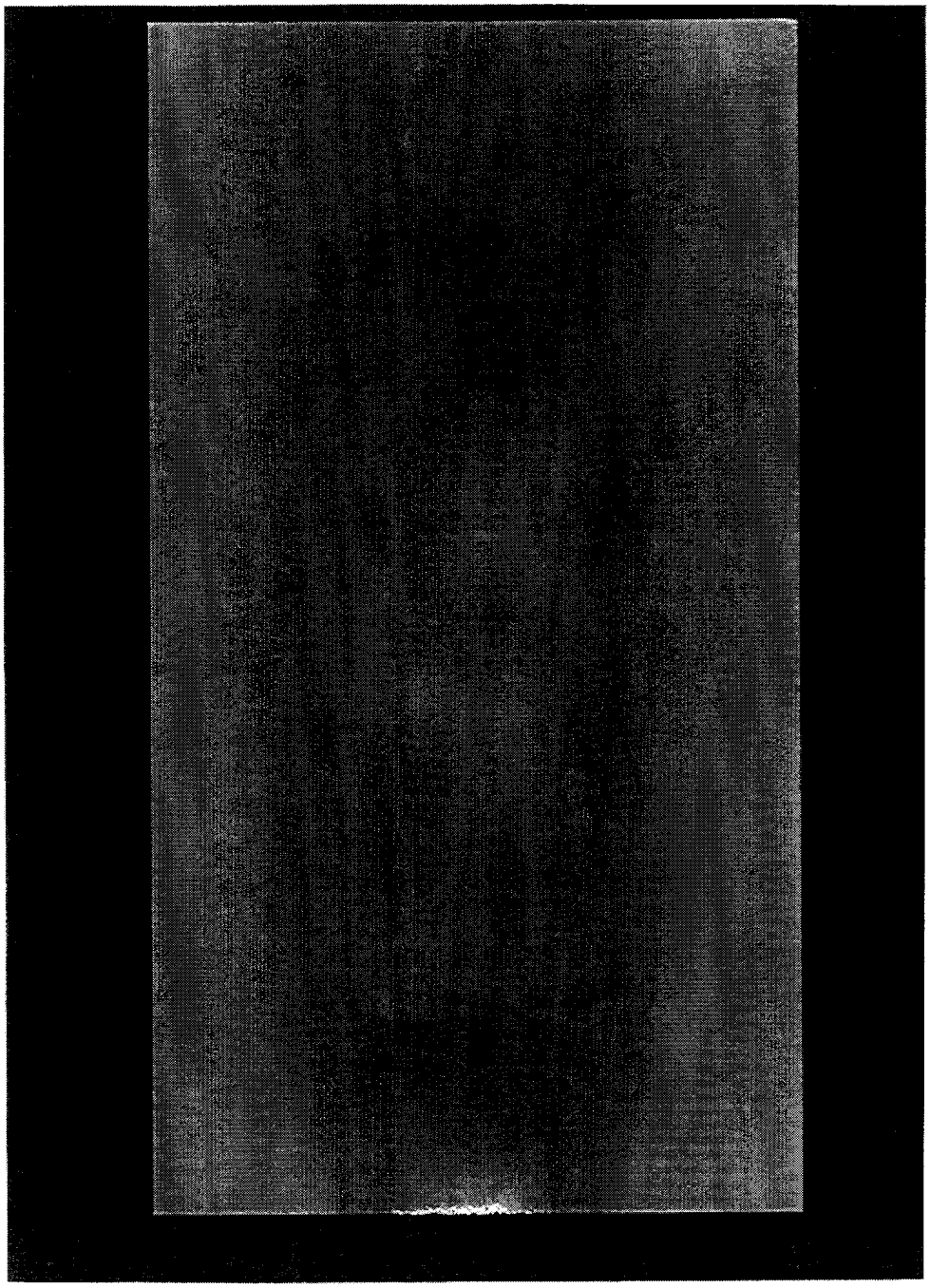


Figure 34. Ratioed Image of the Wind-off and Wind-on Images for the Flat Plate /Jet Interaction at 80 psig

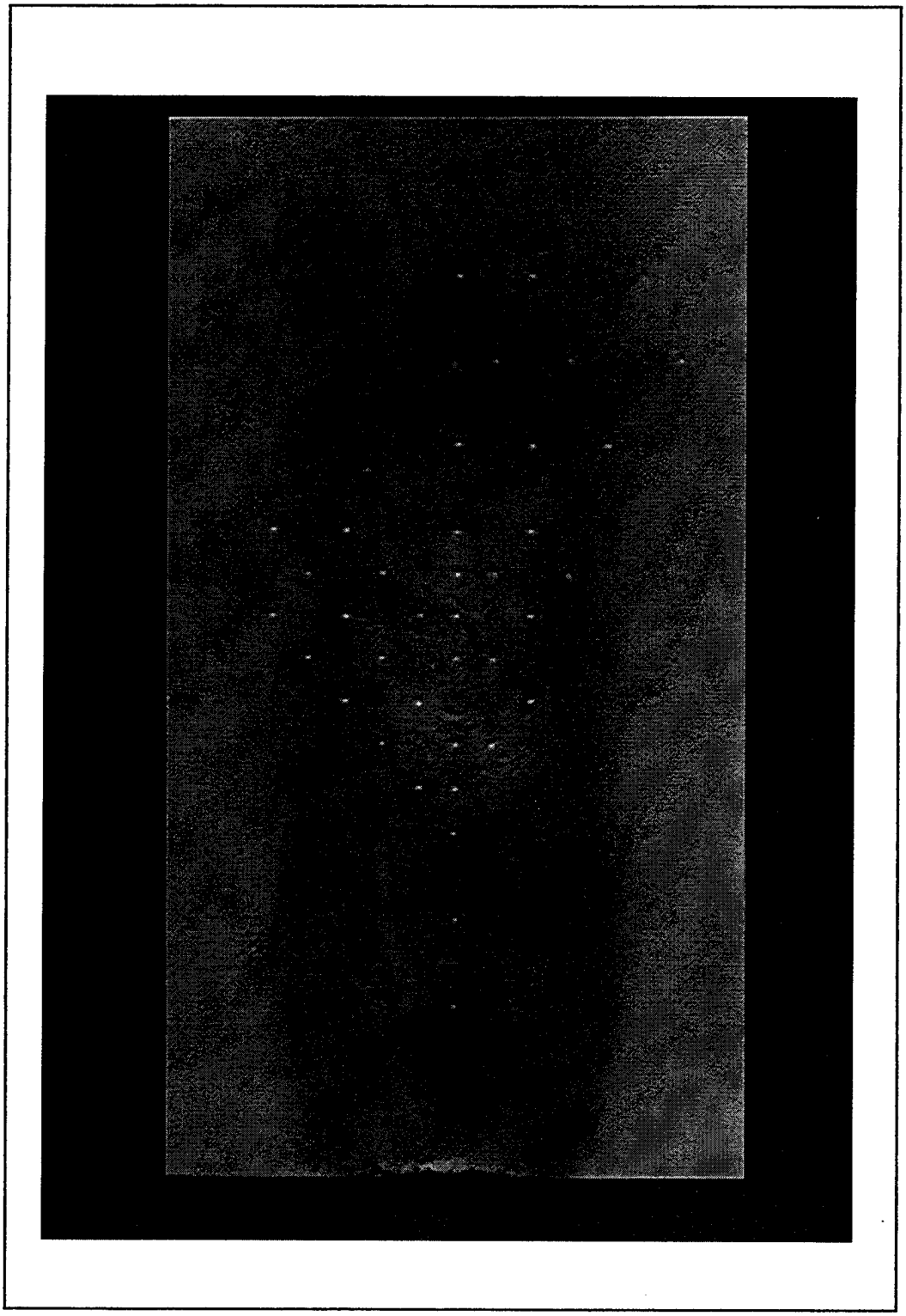


Figure 35. Result of a Ratioed Image Following Improper Registration Technique

b. Calibration

Two methods were available to calibrate the intensity ratio map, the intent of which was to obtain the sensitivity coefficients for the Stern-Volmer equation and establish the pressure map.

The first method, termed "*a prior*", involved calibrating a paint sample in a controlled pressure and temperature chamber. Using the data obtained from the chamber, and knowing the temperature of the model surface, the appropriate values for the Stern-Volmer coefficients could be found [Ref. 7:p. 7].

The second method, termed *"in situ"*, which was the method employed in the present work, used the pressure obtained using a conventional pressure tap in the model surface and compared this with the intensity from the luminescent paint adjacent to the tap. Using data from a number of taps, the sensitivity coefficients were obtained by a least-squares linear fit. The coefficients A and B, being functions only of temperature, were good over that portion of the surface which was at the same temperature as the area containing the pressure taps. [Ref. 7:p. 10]

The approach used to produce pressure data from the ratioed image was similar to that used by Kavandi [Ref. 9:p. 94]. This entailed averaging the data from five adjacent rows of pixels near the pressure taps to produce a single row of data. (This, has the effect of averaging a total of five hundred images together.)

To do this, the ratioed image was loaded five times into consecutive frame buffers of the frame-grabber board. Each successive image was then vertically offset by

one pixel row with respect to the previous image, i.e., the first image remained unmodified, the second image was shifted one pixel row down in its frame buffer with respect to the first image, the third image shifted two pixel rows down with respect to the first image, etc. The five buffers were then averaged. Each row of pixels in the resultant image, with the exception of the first five and the last five rows of the image, was then an average of the corresponding row in each of the five images. A row of pixels close to the pressure taps was then selected to serve as calibration data. Figure 36 shows the data from the selected line of pixels for the flat plate in the underexpanded jet at 80 psig, prior to averaging with four adjacent lines of pixels. Figure 37 shows the data for the same line after the averaging procedure. [It is noted that the "spike" on the left side of the graph is due to paint that has separated from the leading edge of the plate]. From an examination of Figure 36 and Figure 37 it can be concluded that the five-row averaging procedure had the effect of reducing the noise level in the distribution with negligible effect on the distribution itself.

The calibration curves that resulted from plotting intensity values against the measured surface pressure at jet stagnation pressures of 65, 80 and 90 psig, are shown in Figures 38, 39 and 40, respectively. All data were obtained using the line of pixels and the line of pressure taps along the centerline of the jet. Two separate linear fits are shown in each of the figures. This was done when it was realized that the data were poorly represented by a single curve, and that large variations in temperature over the surface of the plate was the probable cause. It is possible that the groups of points which correlate

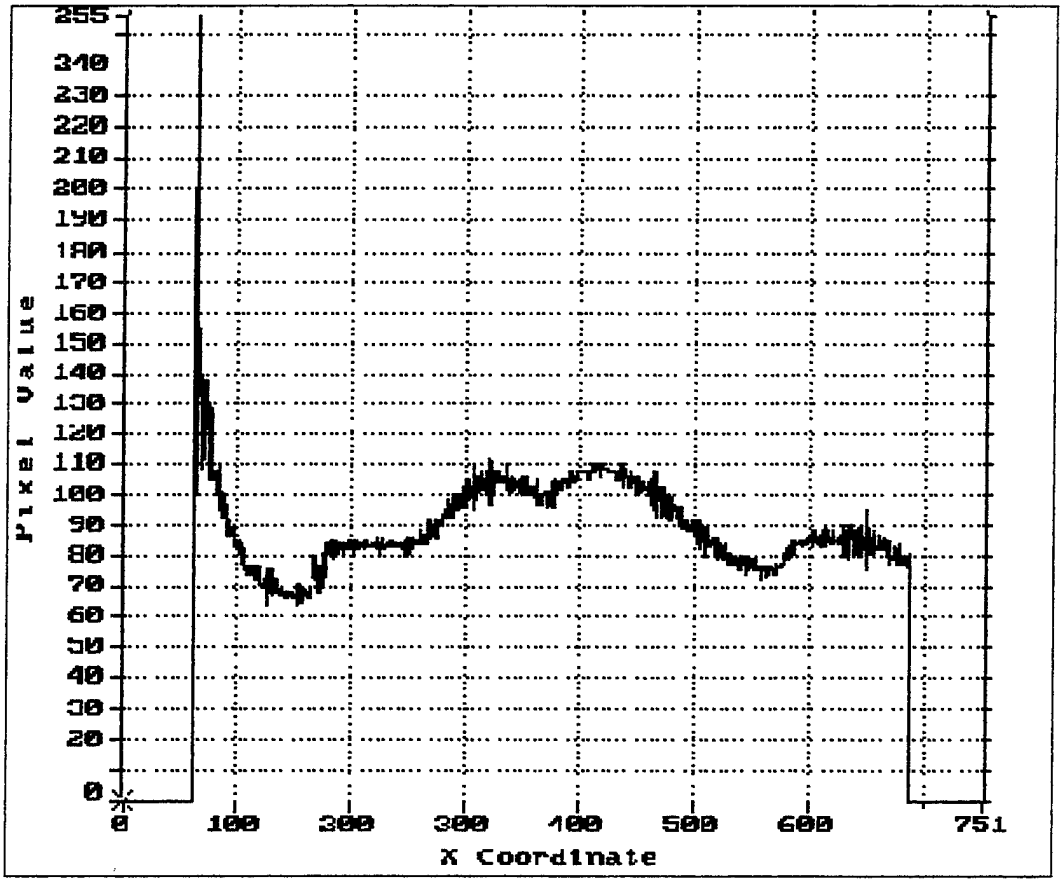


Figure 36. Calibration Line of Pixels for the 80 psig Case Prior to Spatial Averaging

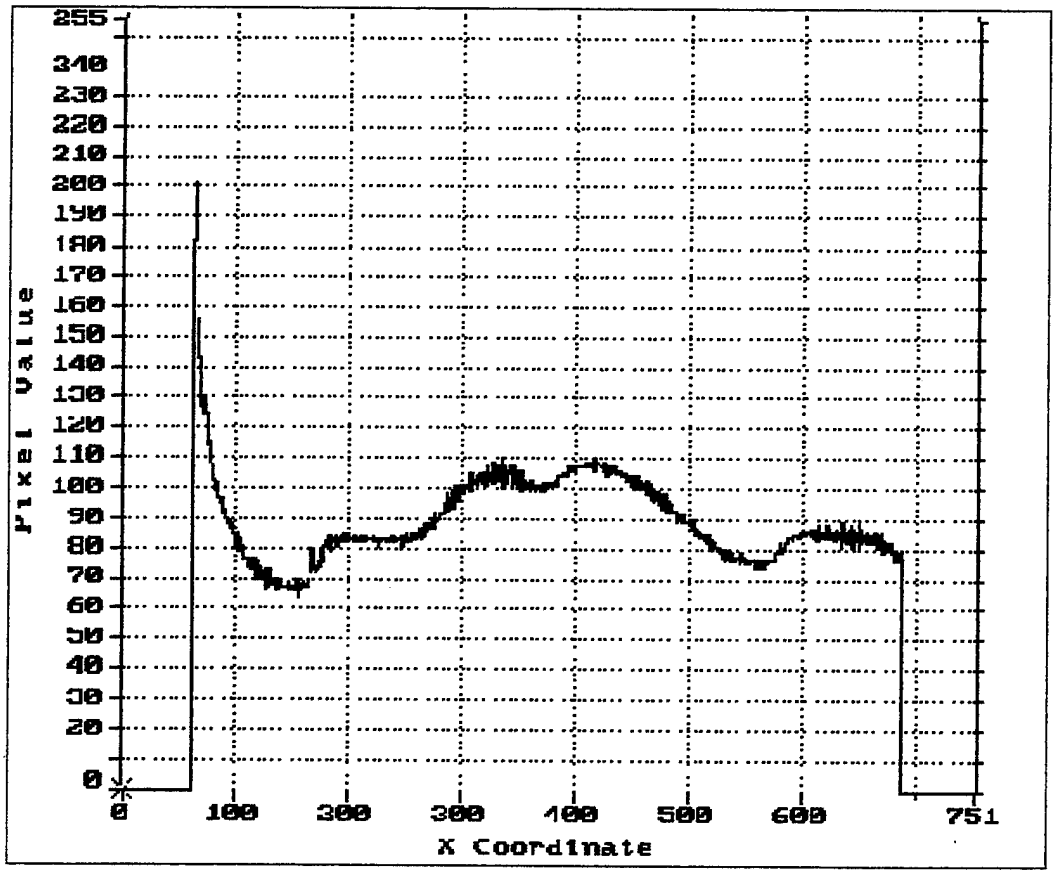


Figure 37. Calibration Line of Pixels for the 80 psig Case After Spatial Averaging

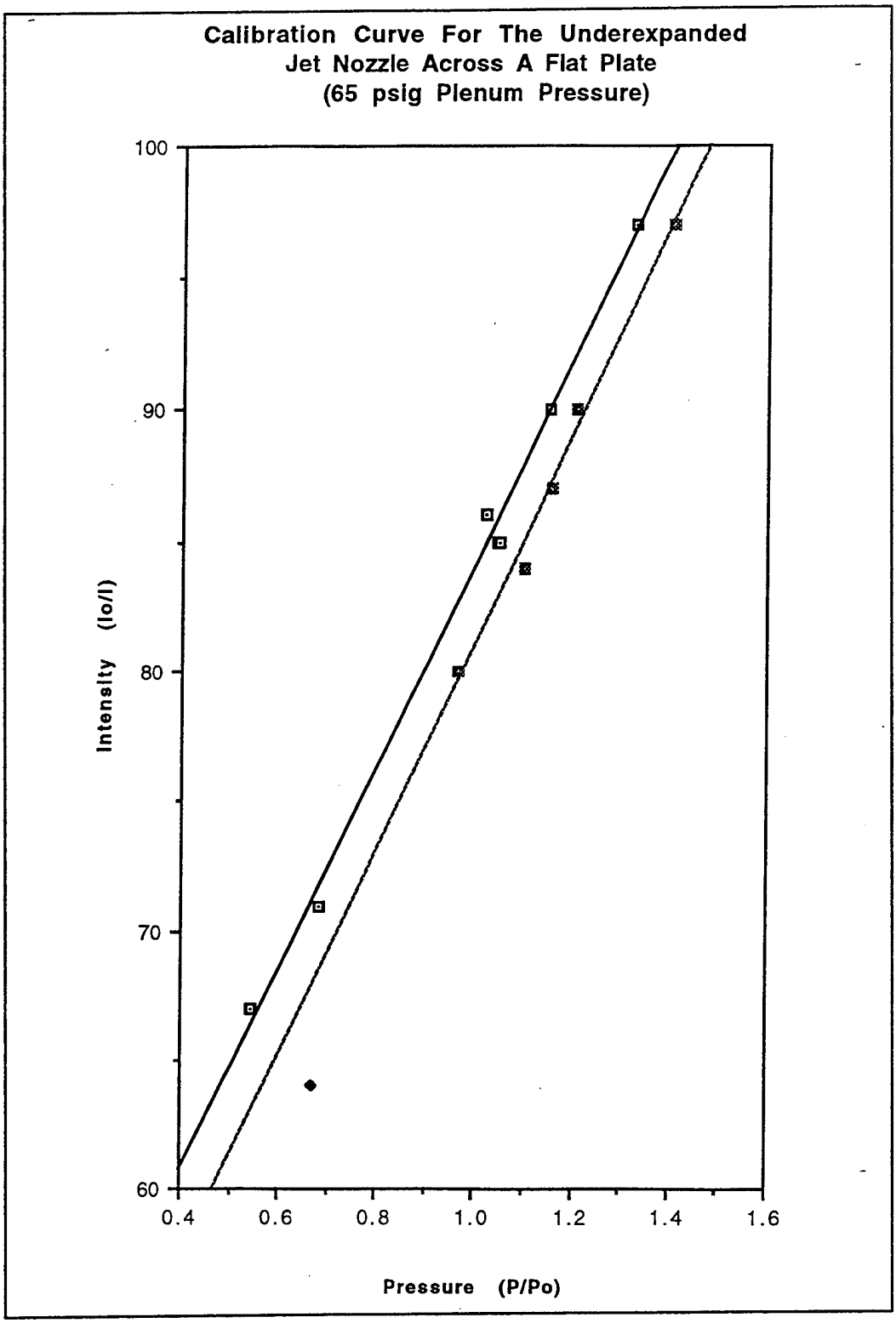


Figure 38. Calibration Curve for the Underexpanded Jet/Flat Plate at 65 psig

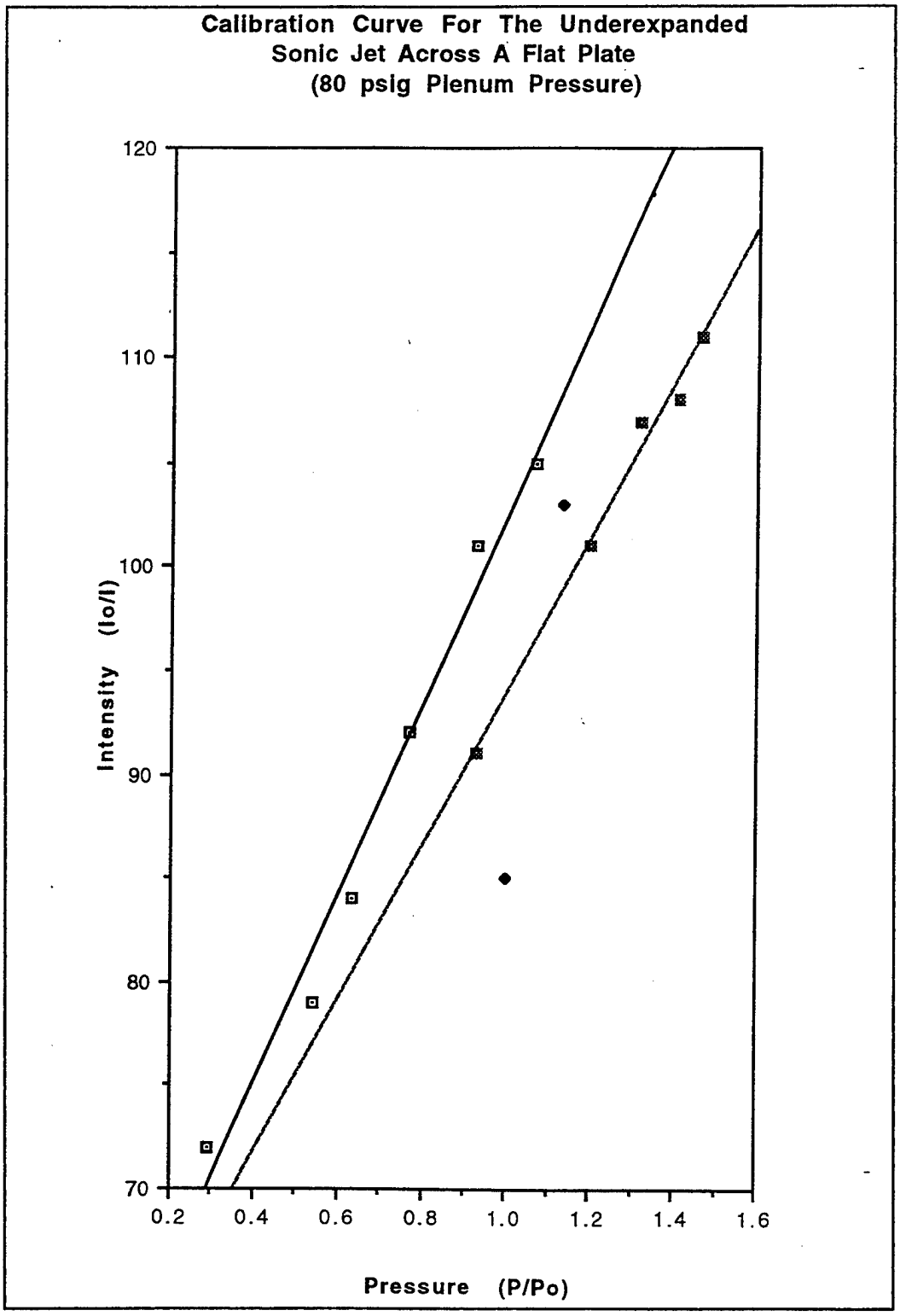


Figure 39. Calibration Curve for the Underexpanded Jet/Flat Plate at 80 psig

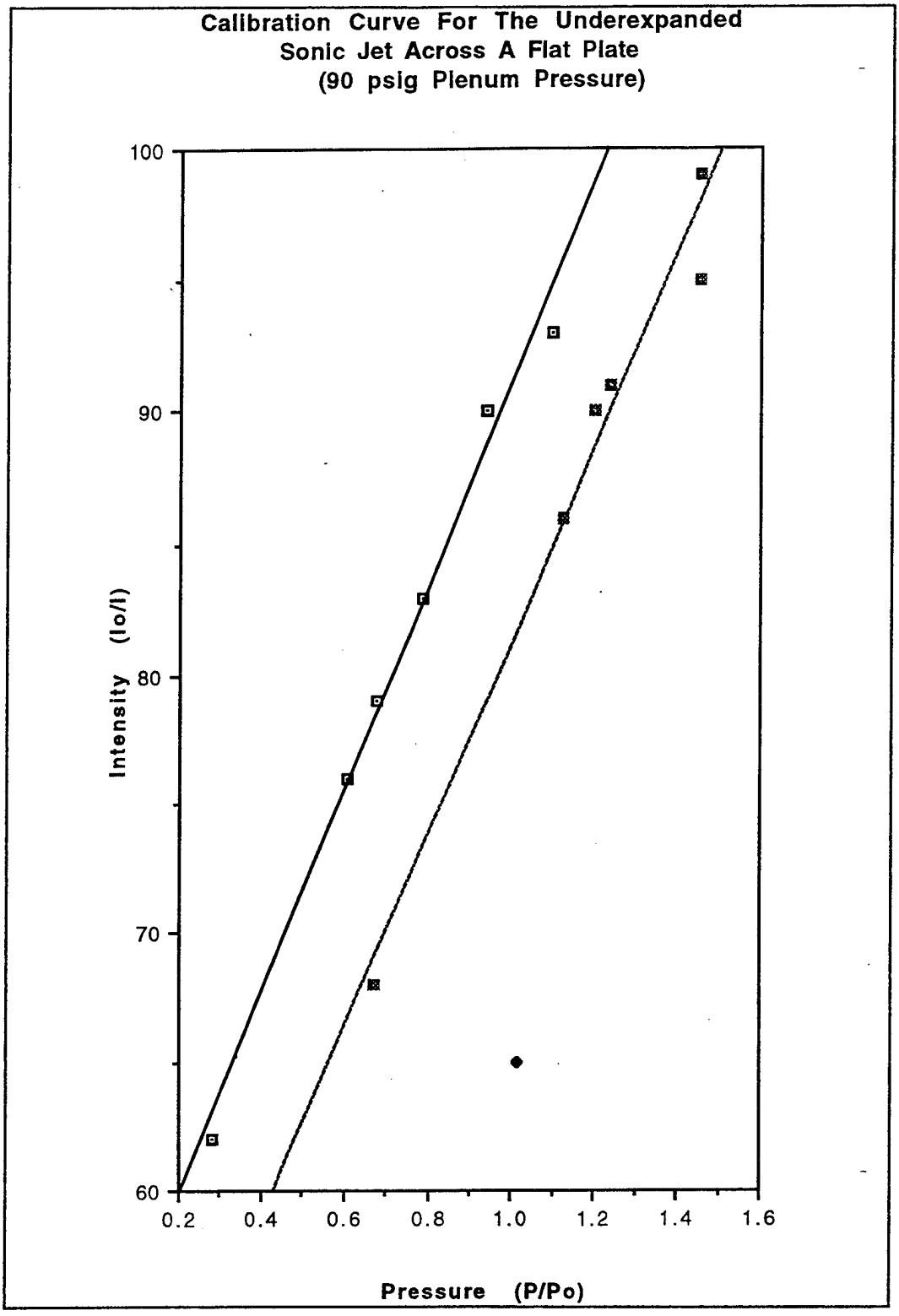


Figure 40. Calibration Curve for the Underexpanded Jet/Flat Plate at 90 psig

linearly are from regions of similar surface temperatures. However, the complexity of the flow over the plate surface, with a three-dimensional separation contained within it, makes the estimation of surface-temperature distribution very difficult. These results clearly indicate the need to measure surface temperature if *in-situ* calibration is to be used.

c. Field Pressure Map

Pseudo-coloring (or "false coloring") of a gray scale image was used to accentuate areas of an image that are not easily discerned by the eye. This was accomplished by providing an assignment of amounts of red, green and blue to a corresponding value of intensity in the gray-scale image. Through the use of look-up tables, the software allowed specification of linear ramps, logarithmic curves, polynomials, gamma correction, inversion and transposition in a pattern or sequence of a non-specific nature. For a gray-scale image the index value is synonymous with its intensity value. Reference 23 may be consulted for further information concerning the manipulation of lookup tables. The color map or sequence that was developed for the present work is shown in Figure 41. The constants A and B represent the minimum and maximum index values of the interval over which the color map was defined. All other index values were assigned the pixel value of zero in the color map. The minimum and maximum index values were found by conducting a histogram on the gray-scale image which gave a breakdown of the pixel intensity values and the frequency of occurrence in the image. The intensity values associated with the pressure-sensitive paint images are usually grouped in an interval between the 0 to 255 index value range.

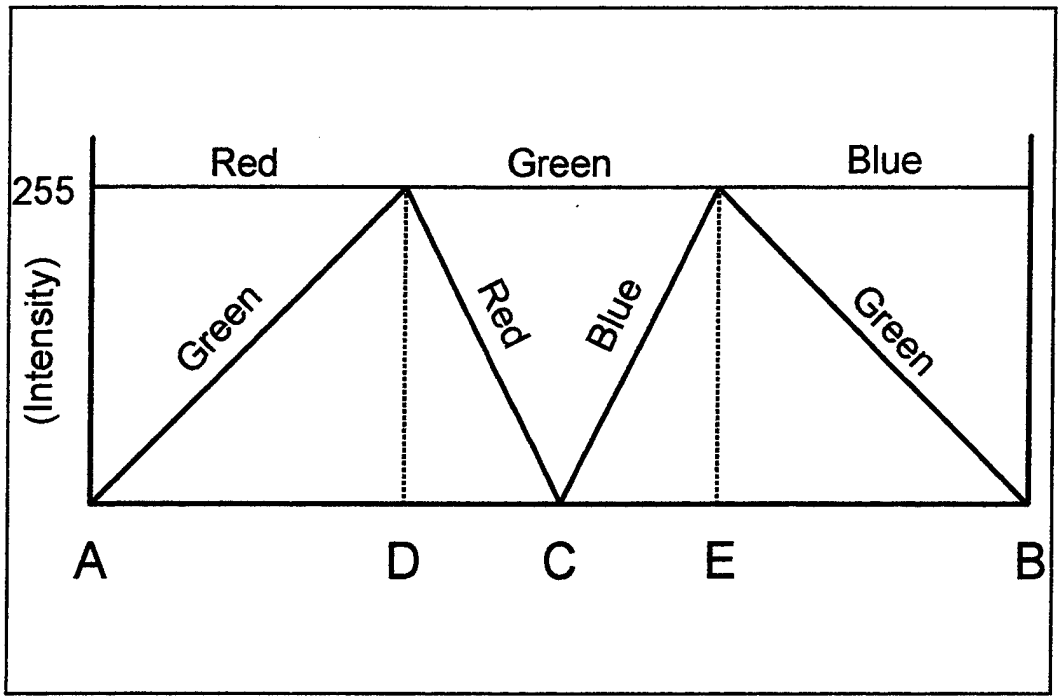


Figure 41. Graphical Representation of the Red, Green, and Blue Lookup Tables

The constant C represents the mid-point of this interval. The constants D and E were varied to obtain the desired bandwidth of the green lookup-table input which influenced the mid portion of the color spectrum.

The final pressure maps for the 65, 80, and 90 psig plenum conditions are given in Figures 42, 43, and 44 respectively. Although quantitative information is not available, the results in Figures 42, 43, and 44 show good qualitative agreement with their schlieren counterparts in Figures 12, 13, and 15 respectively.

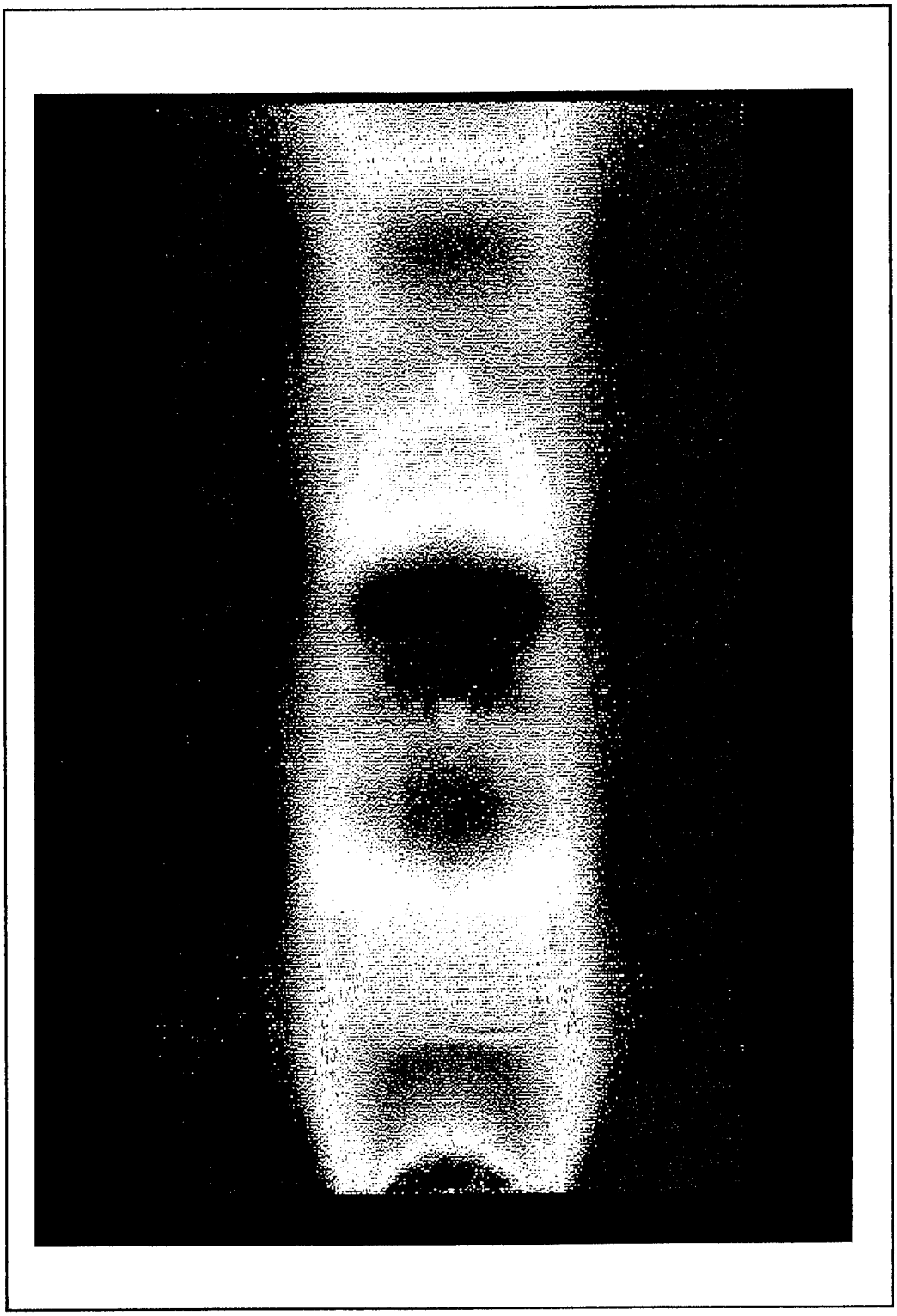


Figure 42. Pressure Map of the Underexpanded Jet at 65 psig Across a Flat Plate

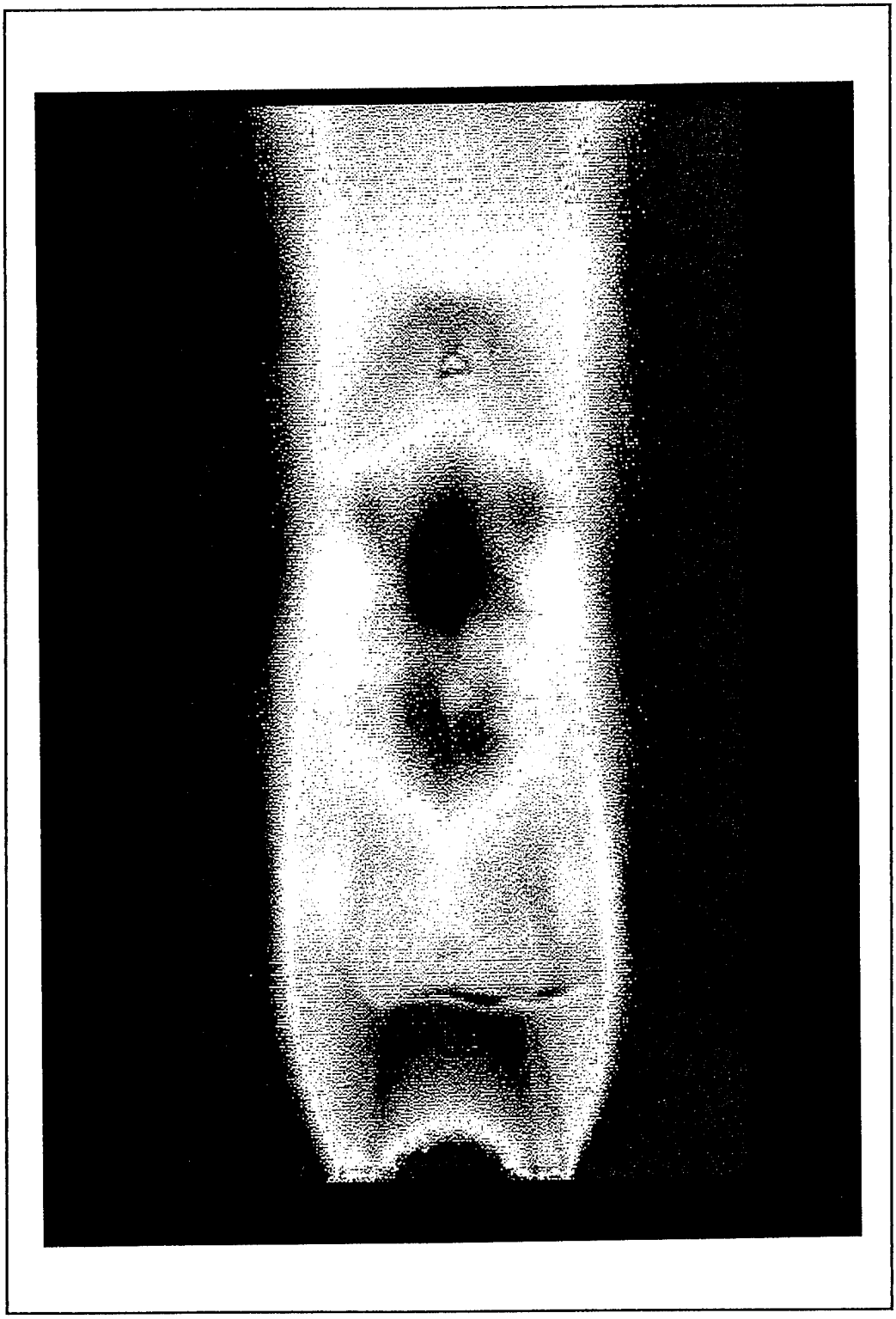


Figure 43. Pressure Map of the Underexpanded Jet at 80 psig Across a Flat Plate

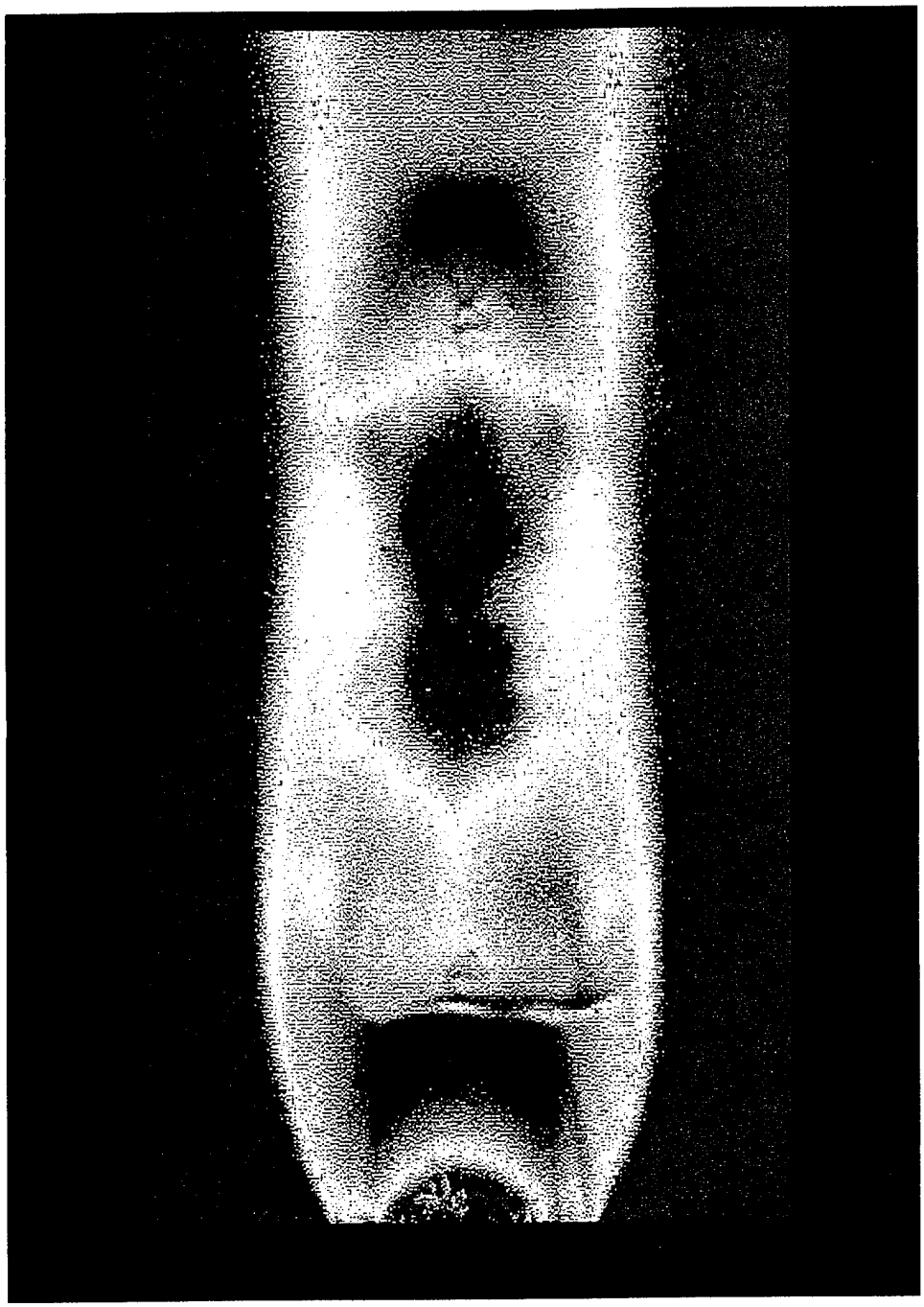


Figure 44. Pressure Map of the Underexpanded Jet at 90 psig Across a Flat Plate

IV. APPLICATION TO SHOCK-BOUNDARY LAYER INTERACTION IN A SUPERSONIC WIND TUNNEL

A. DESCRIPTION OF FACILITY

The supersonic wind tunnel, located in Bldg. 216 of the Gas Dynamics Laboratory [Bldg. 216] at the Naval Postgraduate School, was of the blow-down type. Supply air was produced by the same supporting facility as the underexpanded sonic jet apparatus. A schematic of the tunnel and supporting facility is shown in Figure 45 while Figure 46 shows a photograph of the wind tunnel.

Air to the tunnel, from a maximum pressure of 300 psi, was controlled by a pneumatic control valve. The control valve used a diaphragm actuator. Regulated instrument air from the supply system was routed to one side of the diaphragm and the controlled pressure, from a tap on the plenum, was connected to the other. This allowed precise control of the plenum pressure. A pressure gauge installed on the plenum provided pressure readout.

The plenum chamber was cylindrical with an internal diameter of approximately 20 inches. With the exception of a splash plate mounted perpendicular to the flow near the entrance of the chamber, the plenum was empty. The flow exited the chamber through a contraction and circular-to-rectangular transition section, into the convergent-divergent

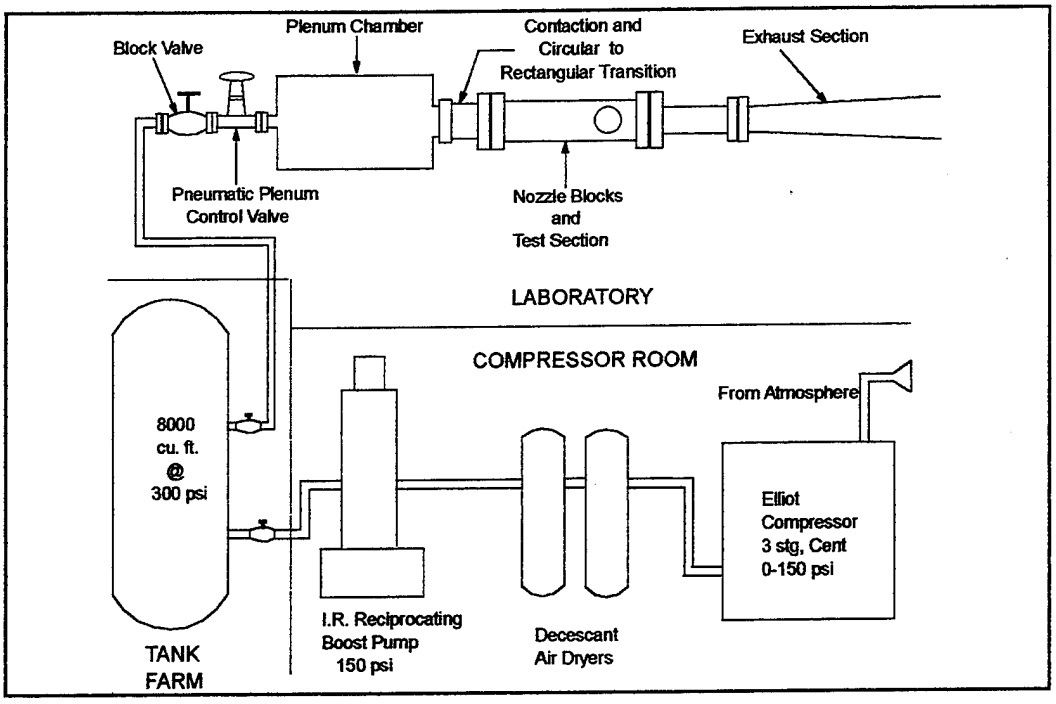


Figure 45. Schematic of the Supersonic Wind Tunnel and Supporting Facility

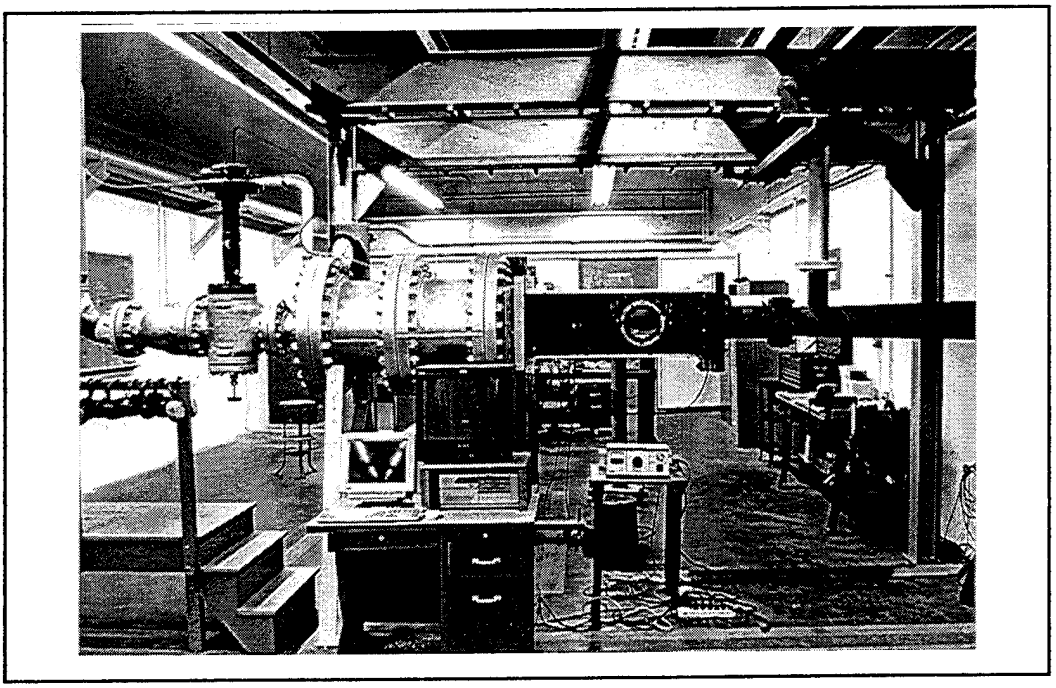


Figure 46. Supersonic Wind Tunnel Apparatus

nozzle. The nozzle and test section,shown schematically in Figure 47, were comprised of a set of two (interchangeable) aluminum blocks forming the contour and two flat plates forming the side walls and enclosing the constant-width section.

The test section was nominally four inches in width and four inches in height. Six-inch diameter circular glass windows on each side of the test section provided optical access. Two small gate valves were mounted on each of the side walls just downstream of the test section. They were used to allow "bleed" and thus control back pressure in order to position the "starting" normal shock in the test section. The flow exited the test section into an exhaust duct which vented to the atmosphere outside the building.

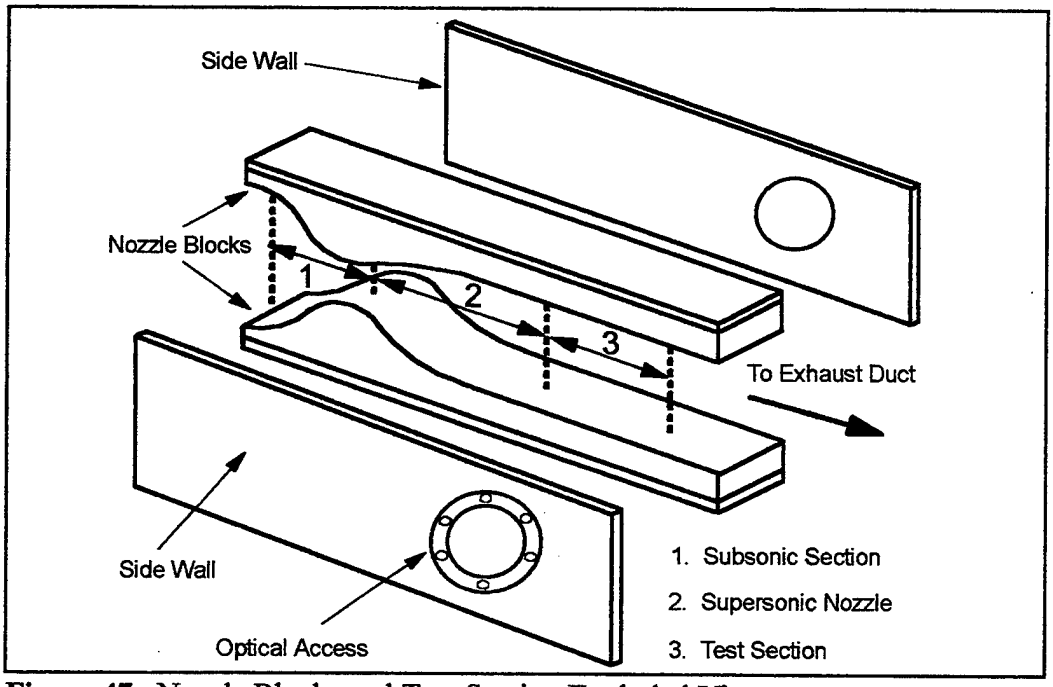


Figure 47. Nozzle Blocks and Test Section Exploded View

1. Nozzle Blocks

The interchangeable pairs of nozzle blocks were each designed to produce a specific Mach number in the test section. For the present study, two Mach numbers, 1.4 and 1.7, were used, since this was the range of Mach number of interest in the proposed study of control of shock-boundary layer interaction. A set of blocks for M=1.4 existed. However, it was necessary to design and manufacture a set of blocks to provide M=1.7. The program described in Appendix E was used to derive the contour for the M=1.7 nozzle. The new blocks were otherwise similar to the existing blocks and were manufactured to the original dramings using the new contour.

a. Performance Evaluation of the Mach 1.7 Nozzle Blocks

To evaluate the new nozzle blocks, several runs at varying plenum pressures were conducted. A series of pressure taps along one side of the tunnel allowed pressure data to be collected. The taps extended approximately four inches upstream of the nozzle throat and downstream to the entrance of the test section. A metal blank containing additional taps was installed in place of one of the test section windows to measure pressures through the test section. One tap downstream of the test section measured the pressure of the exiting flow.

The data acquired indicated that the normal shock associated with the nozzle starting process rapidly passed through the test section into the exhaust duct as soon as the operating pressure ratio decreased below the first critical condition. Unlike with the M=1.4 blocks, the bleed valves on the sides of the tunnel could not be used to position the

shock. It was realized that some form of blockage would have to be introduced into the passage at some point downstream of the test section in order to "set" the shock in the test section.

The mounting points for the gate valves, which were located three inches downstream of the test section and were aligned such that their centerlines coincided with each other, were adapted so that circular rods of varying diameter could be installed across the tunnel. A total of four rods was used. Operating the tunnel at 75 psi plenum pressure, the static pressure distribution was recorded for each configuration. The effect of rod diameter on shock position is clearly seen in Figure 48.

The 3/8 inch diameter rod was found to place the shock just prior to the test section. To position and control the shock precisely in the center of the test section, a means of bleeding off mass flow was developed. The solid rod was replaced by a 3/8 inch outside diameter tube. A series of 11/64 inch holes was drilled through the tube wall, in a line along its 4-inch length. The tube was then mounted between the gate valves with the holes aligned with the flow. This arrangement allowed a controlled mass flow to pass through the holes into the tube and out of the tunnel via the gate valves. The gate valves could be adjusted to vary the amount of outgoing mass, thus moving the shock to the desired position in the test section. A schematic of this arrangement is shown in Figure 49 while Figure 50 shows a photograph of the bleed-off tube mounted in the tunnel.

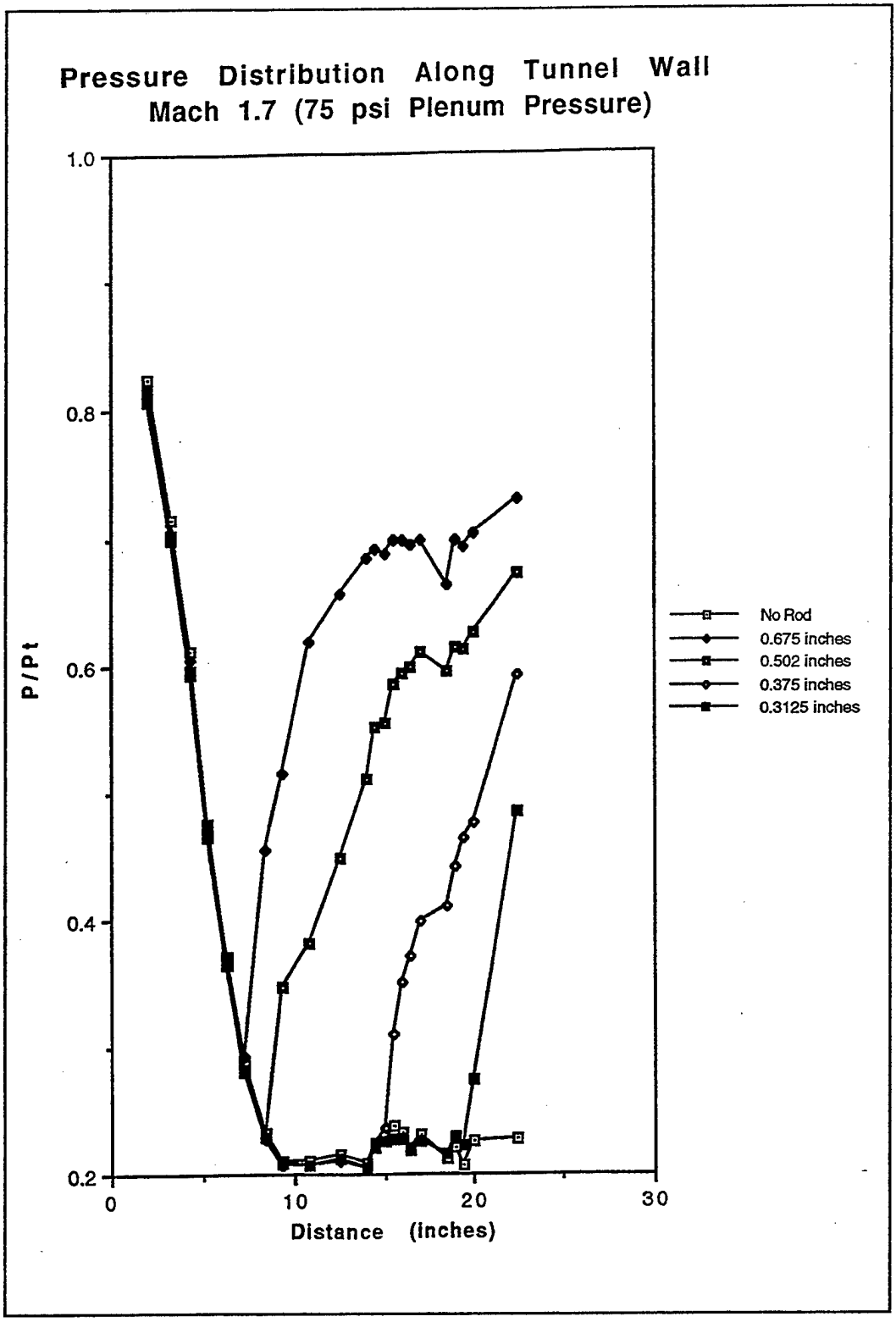


Figure 48. Tunnel Pressure Distributions as a Result of Varying Rod Diameters

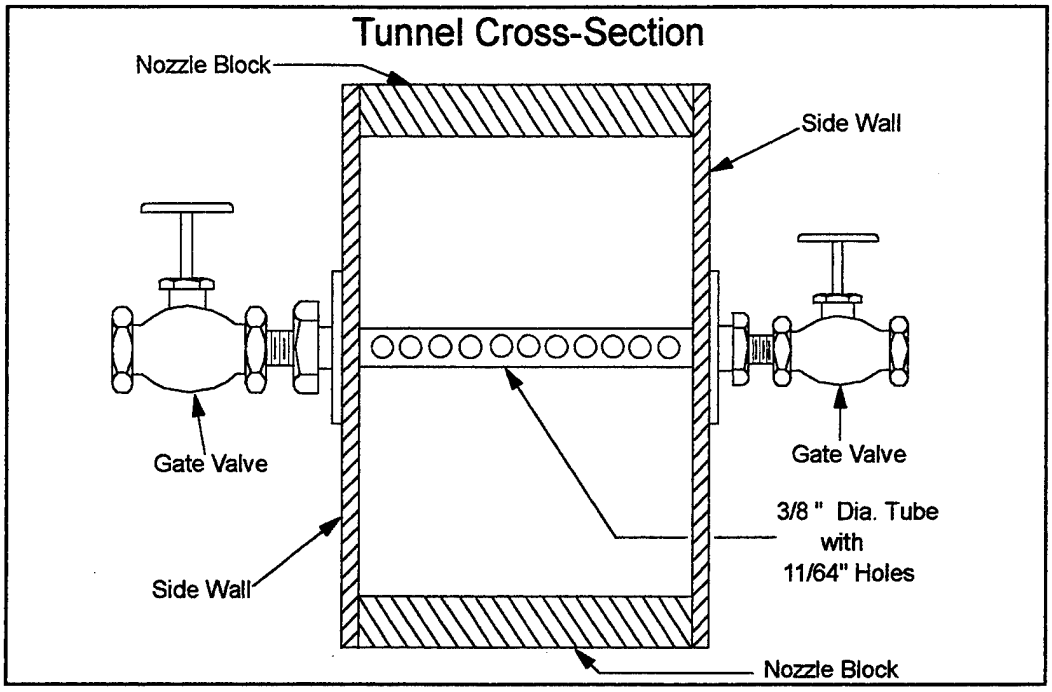


Figure 49. Cross-Sectional View of the Mass Bleed-Off System

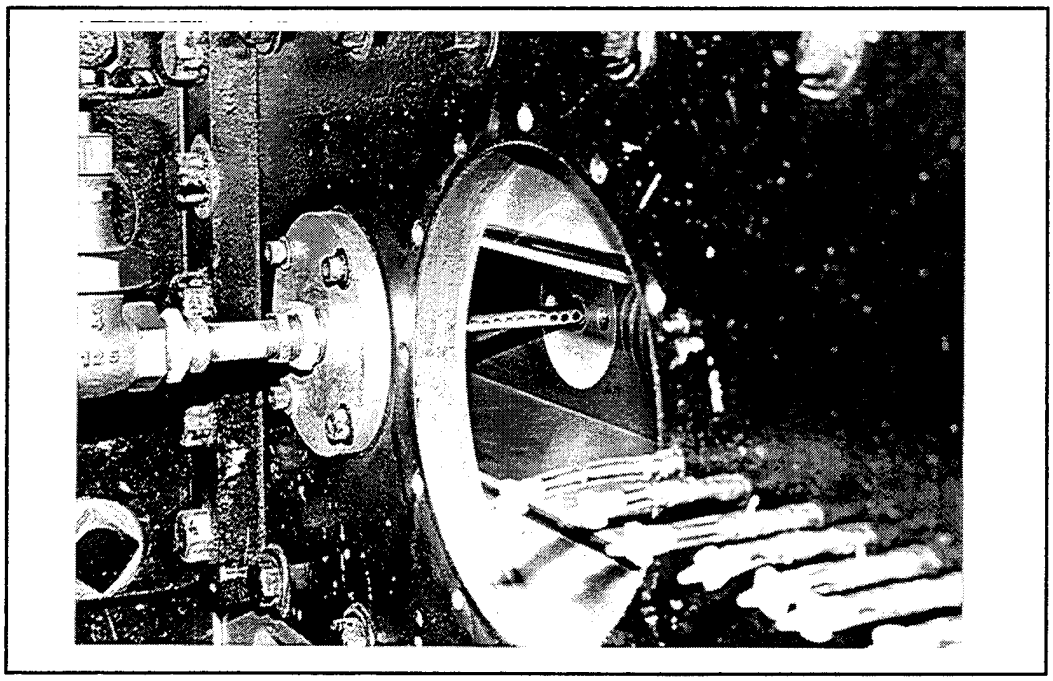


Figure 50. Mass Bleed-Off Tube Mounted in the Tunnel

B. INSTRUMENTATION

The metal blank, containing eleven pressure taps, and used as described above to measure the pressure distribution in the test section, was used as the model surface on which to observe the interaction between the starting normal shock and the nozzle boundary layer using pressure-sensitive paint. The metal blank was installed on one side of the test section and a six inch glass window was installed on the other. Concern for the spectral transmittance of the glass window led to an analysis of the glass for the range of 350 nm to 700 nm using a spectrometer. The results of the test, shown in Figure 51, indicated that the transmittance levels were satisfactory for the current work.

The optical measurement system was the same as was used for the underexpanded jet study described in chapter three. A schematic of the setup is shown in Figure 52.

C. EXPERIMENTAL PROCEDURE

It was found that the shock-boundary layer interaction in the test section was inherently unsteady. This precluded the use of the procedure outlined in chapter three for acquiring the wind-on data. That method required the event of interest to be steady and repeatable, thus enabling one hundred images to be taken over a series of ten runs. The approach taken for the unsteady process was simply to create as many image buffers as possible for a single sequence, and to execute this sequence in the shortest period of time.

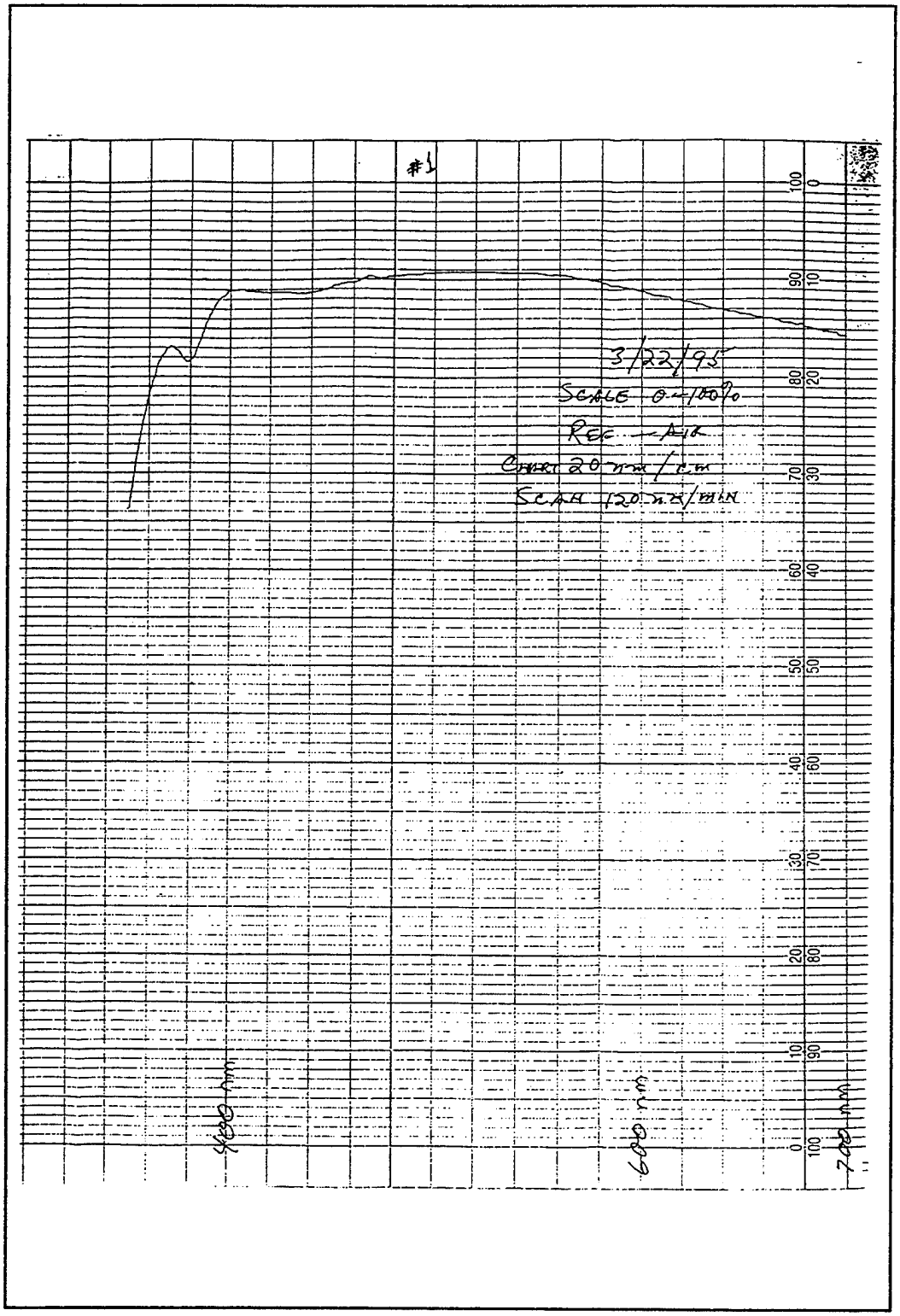


Figure 51. Spectrometer Results for the Optical Window

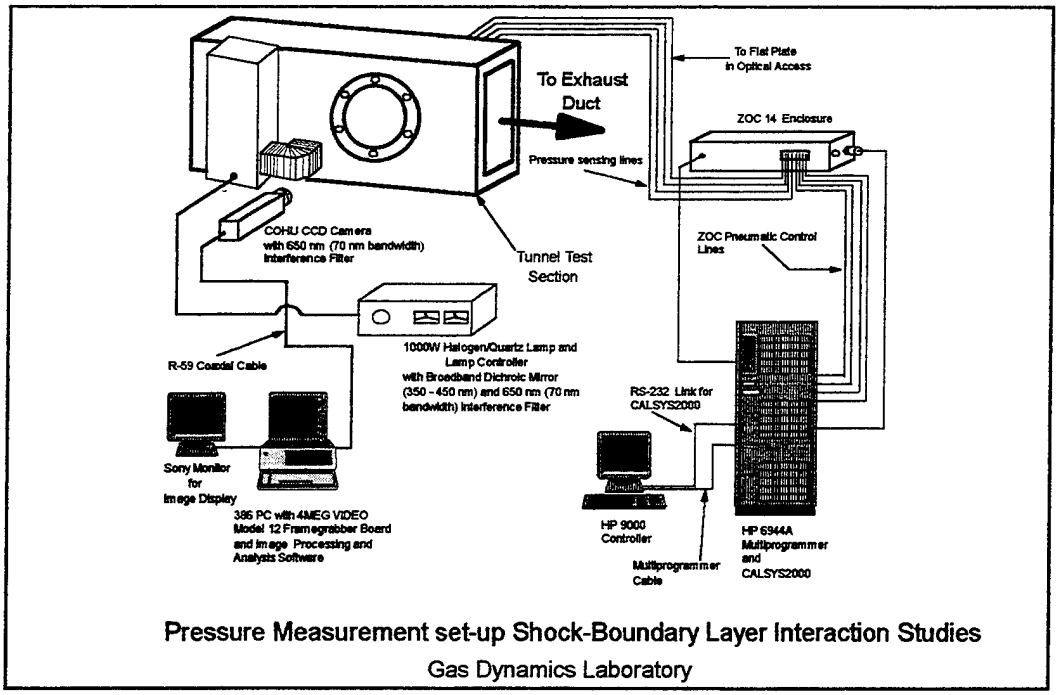


Figure 52. Instrumentation Setup for the Supersonic Wind Tunnel, Shock-Boundary Layer Experiment

The maximum number of image buffers that could be created for image capture was a function of video resolution. To maximize the number of available buffers it was necessary to minimize the video resolution. To accomplish this, the camera was focused on the test section so that the surface of the metal blank was clearly displayed on the video monitor. The video resolution was set at maximum (752 x 480) at this point. With the video resolution menu displayed on the computer screen, the parameters controlling the numbers of pixels and pixel lines were iteratively decreased until the camera's field of view shown on the video monitor exhibited only the test surface, the rest of the field of view being deleted. The resulting resolution was 600 pixels per line and 340 lines of video or 600 x 340 (assuming "Interlace: Use Distinct (2) Fields?" is active) which allowed 21 image buffers to be available for image capture. Since McDonnell-Douglas [Ref. 6:p. 8]

had shown that averaging data from as few as eight images significantly reduced the noise on the signal, it was concluded the 21 images would be sufficient.

The period required for a sequence to be completed was based on the time interval specified between consecutive samples, the shortest interval being 1/30 of a second. Since a video frame was generated every 1/30th of a second by the camera, the total time to execute a sequence containing 21 image buffers was 1.37 seconds.

The experiment began with the Mach 1.4 blocks installed in the tunnel. Using the shadowgraph technique, the normal shock was positioned in the test section by adjusting the backpressure through the gate valves, while the plenum pressure was set at 30 psi. When the valves were properly adjusted the tunnel was shut down, the metal window blank with pressure sensitive paint applied was installed, and the camera and illumination system were located eight inches away from the optical glass window. A real-time image of the test section was displayed on the image monitor, and the parameters to execute the desired sequence described above, were input into the computer. A cover was placed over the test section to prevent photodegradation of the paint, the light source was turned on and allowed to "ramp up" and stabilize. The wind tunnel was then started, the plenum pressure set at 30 psi, and the laboratory lights were turned off. The wind-on data were captured while pressure data were taken simultaneously using the CALSYS2000 data acquisition system. Twenty samples per port were taken at a sampling rate of 10,000 Hz. Three such runs were conducted. Between each run, wind-off and dark-current images were collected. Temperatures for the tunnel and the test plate were not available.

The Mach 1.7 nozzle blocks were then installed with the mass bleed-off system described earlier. With the plenum pressure set at 70 psi the shadowgraph was again used to position the normal shock. With the test plate installed, three runs were conducted in a similar manner to that described for the M=1.4 blocks. The data were post-processed using the techniques described in chapter three.

D. DISCUSSION AND RESULTS

The flow structure expected to be produced by the interaction between a normal shock and a turbulent boundary layer is shown schematically in Figure 53. The pressure-sensitive paint technique was to be used to measure the surface pressure through the interaction region. Previous work by Perretta [Ref. 24] involved a study of the flow across the shock structure shown in Figure 53, and the resulting separation, for the given M=1.4 tunnel configuration used in the present study.

For the M=1.4 case, the pressure map obtained is shown in Figure 54. It can be seen that the interaction was nearly two-dimensional. To illustrate the distribution of the pressure rise, a line of pixel intensity values taken along the plate is shown in Figure 55. The profile resembles those of Kooi [Ref. 25:p. 30-8] for turbulent boundary layer separation on a flat plate due to normal shock interaction. The steepest slope of the curve indicates the start of the interaction, according to Kooi's work. The separation point can be identified as that point in the curvature where either a discontinuity in the curvature

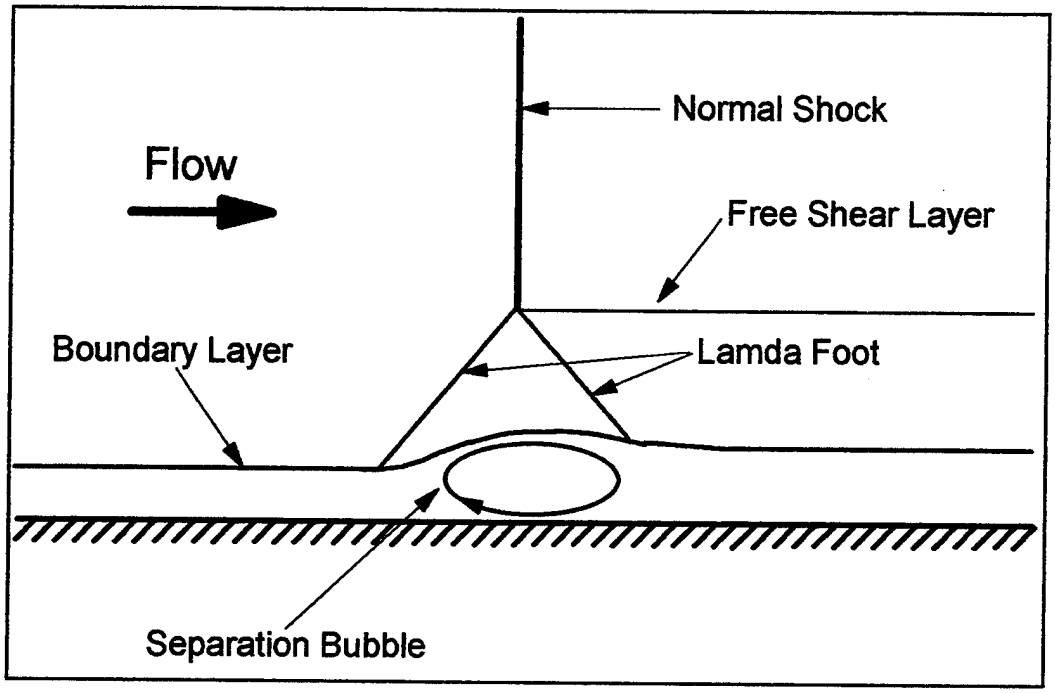


Figure 53. Schematic of the normal shock-boundary layer interaction

exists or the degree of change in curvature is much less compared to that of the start of the interaction, indicating a much slower rise in pressure. From the distribution of the intensity values, this point is difficult to determine. This can be attributed to oscillations of the normal shock, and the pressure-sensitive paint's poor dynamic response to these changes, causing an averaging effect and eliminating changes in curvature from the curve. Also, the time to execute the data collection sequence was much longer than the oscillation period of the shock, adding to the error in the results. The absence of a plateau in the intensity distribution suggests that the separation region was very short.

In the case of M=1.7, the determination of separation is more definite. The pressure map is shown in Figure 56 while the corresponding streamwise line of pixel-intensity

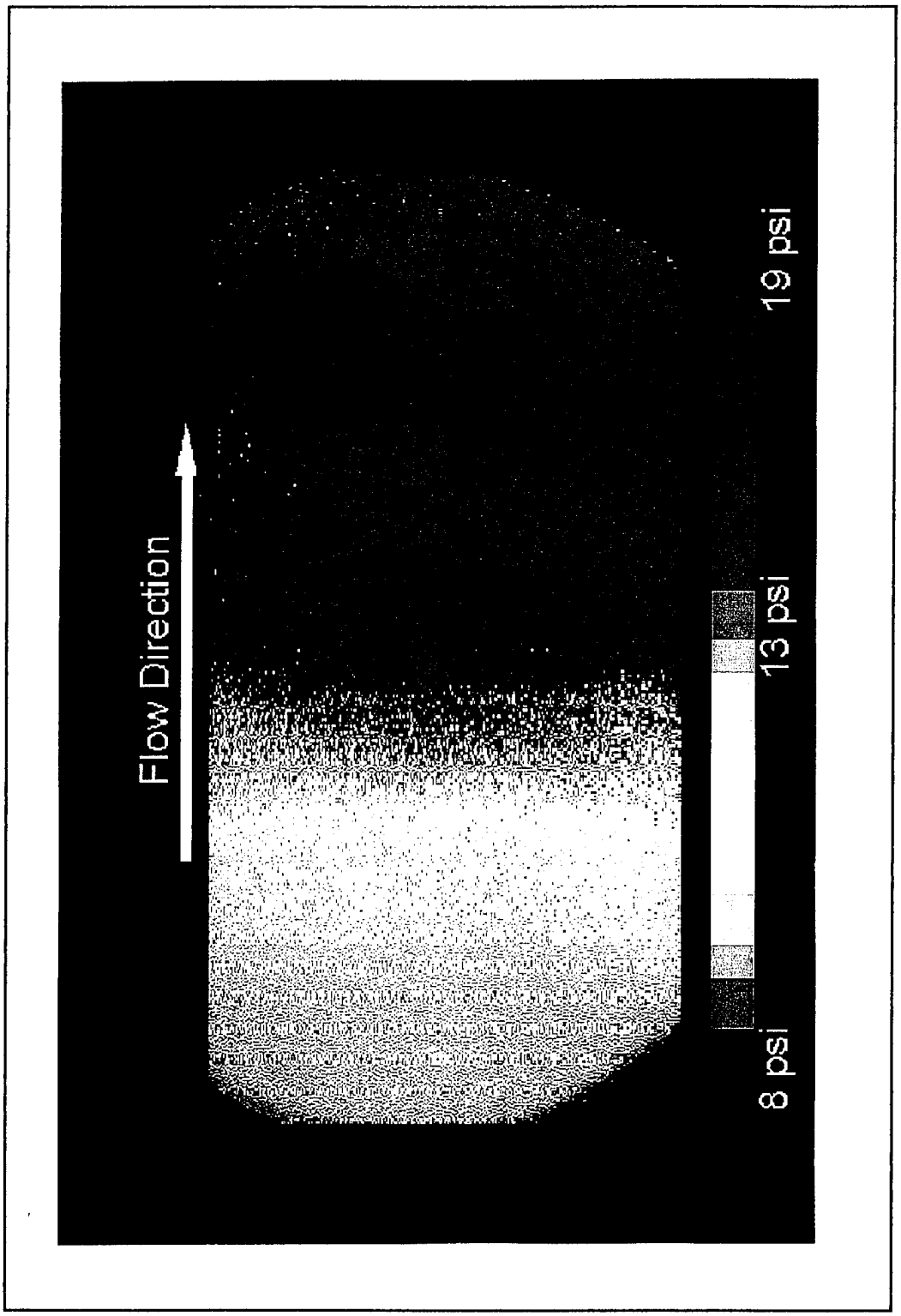


Figure 54. Mach 1.4 Pressure Map of the Shock-Boundary Layer Interaction

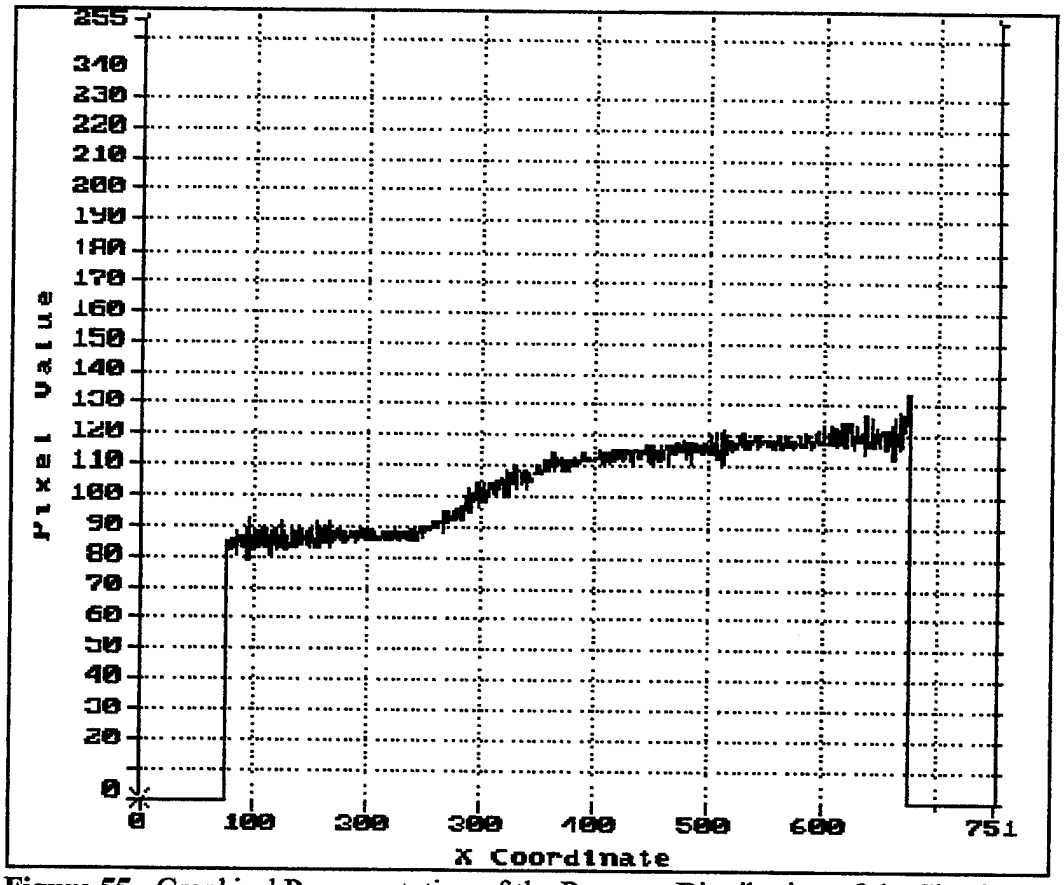


Figure 55. Graphical Representation of the Pressure Distribution of the Shock-Boundary Layer Interaction at Mach 1.4

values is displayed in Figure 57. The intensity curve here shows a definite plateau, a region of nearly constant pressure, which is an indication of an extended length of separation. This region corresponds to the area illustrated by the narrow green band in the pressure map of Figure 56.

The calibration curves for the M=1.4 and M=1.7 data are given in Figures 58 and 59 respectively. In contrast to the calibration curves developed for the underexpanded jet/ flat plate data, areas of similar temperature are more easily identified in the shock-boundary layer experiment. The data points upstream and downstream of the normal shock have been linearly approximated separately since there was a near

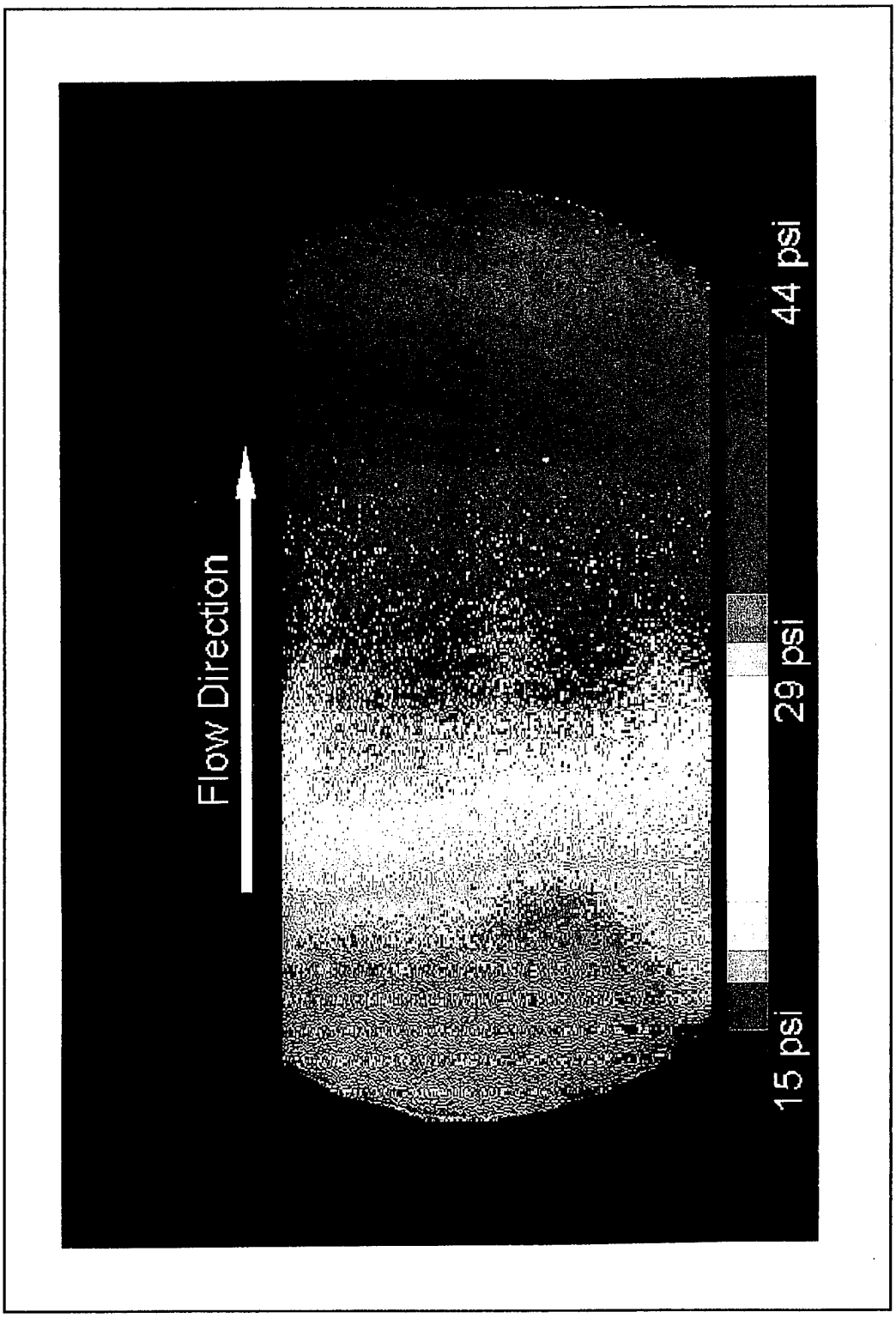


Figure 56. Mach 1.7 Pressure Map of the Shock-Boundary Layer Interaction

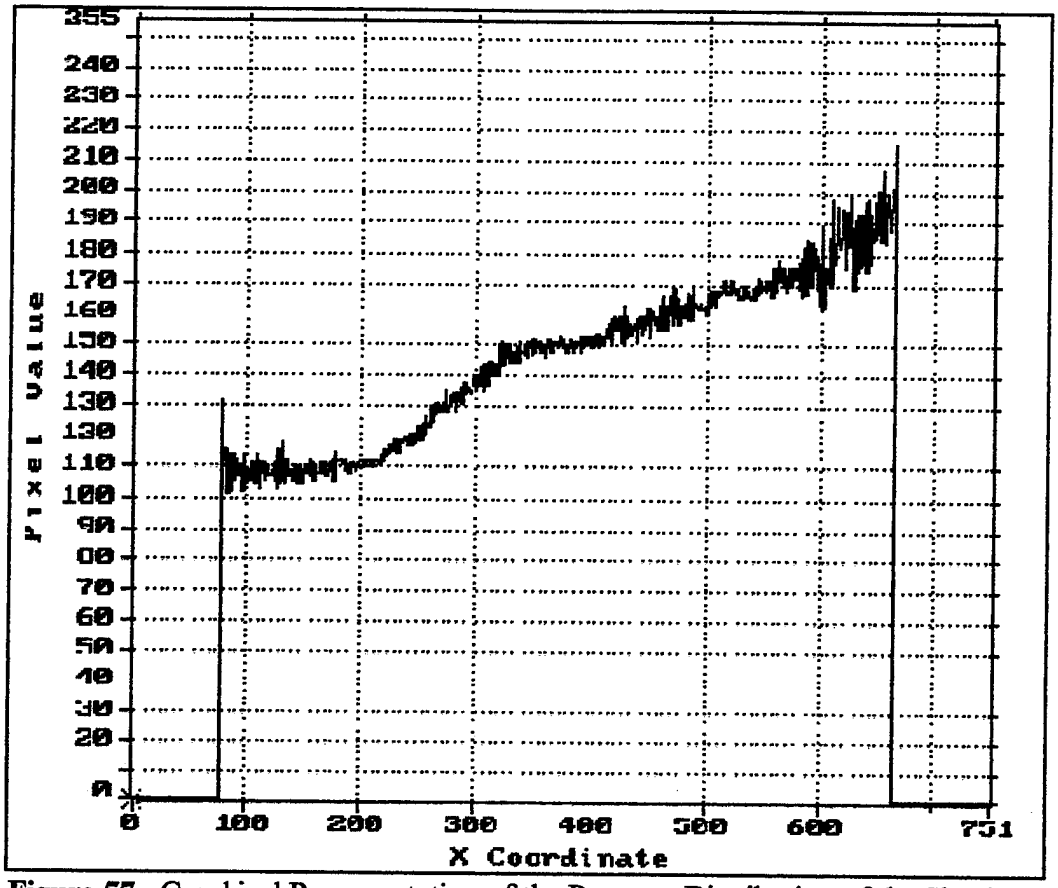


Figure 57. Graphical Representation of the Pressure Distribution of the Shock-Boundary Layer Interaction at Mach 1.7

discontinuity in temperature and heat transfer at the shock impingement location. There is seen to be a change in the sensitivity of the paint to pressure change which occurs at the shock. The paint is more sensitive downstream of the shock, which is consistent with the occurrence of higher temperature.

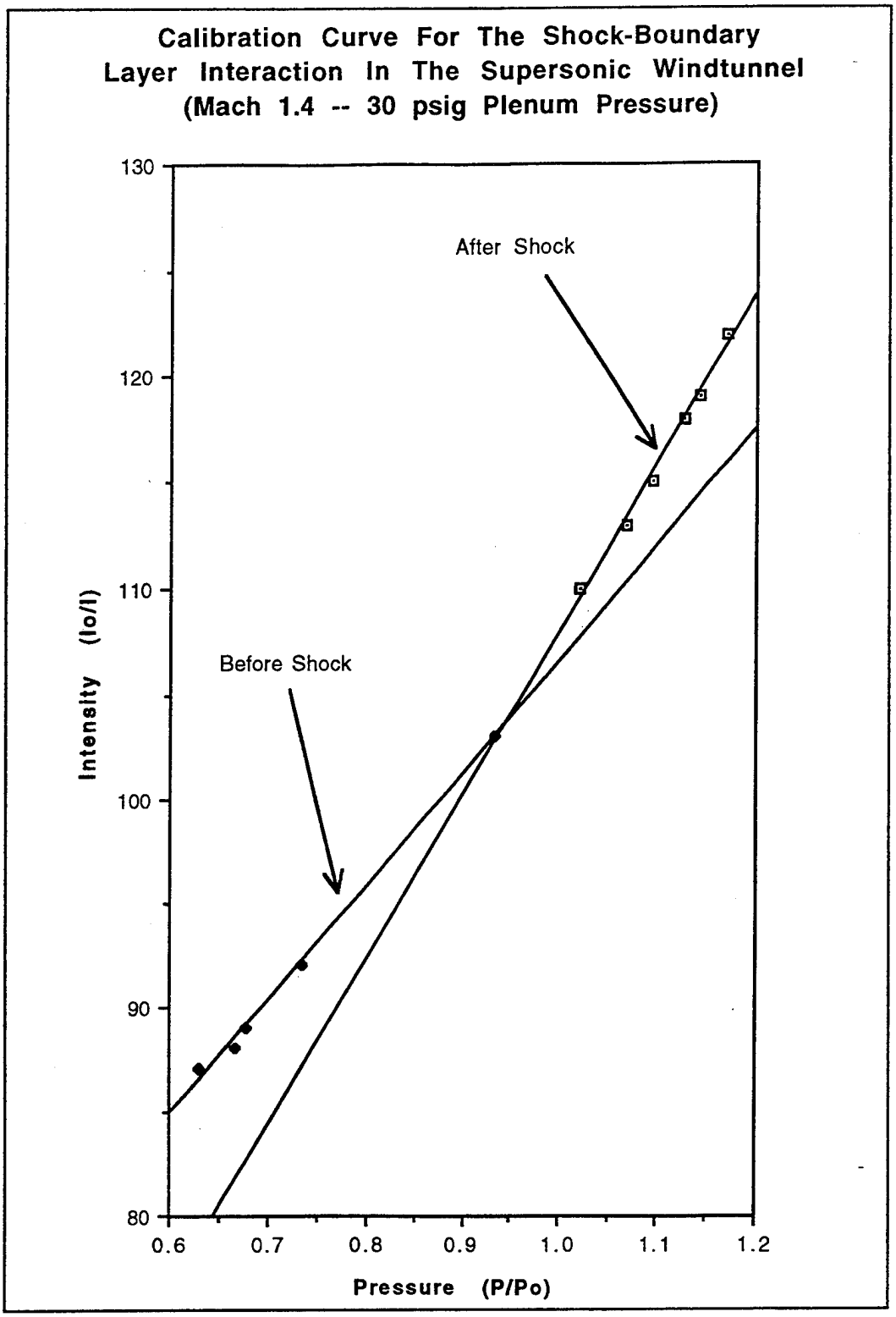


Figure 58. Calibration Curve for the Mach 1.4 Interaction

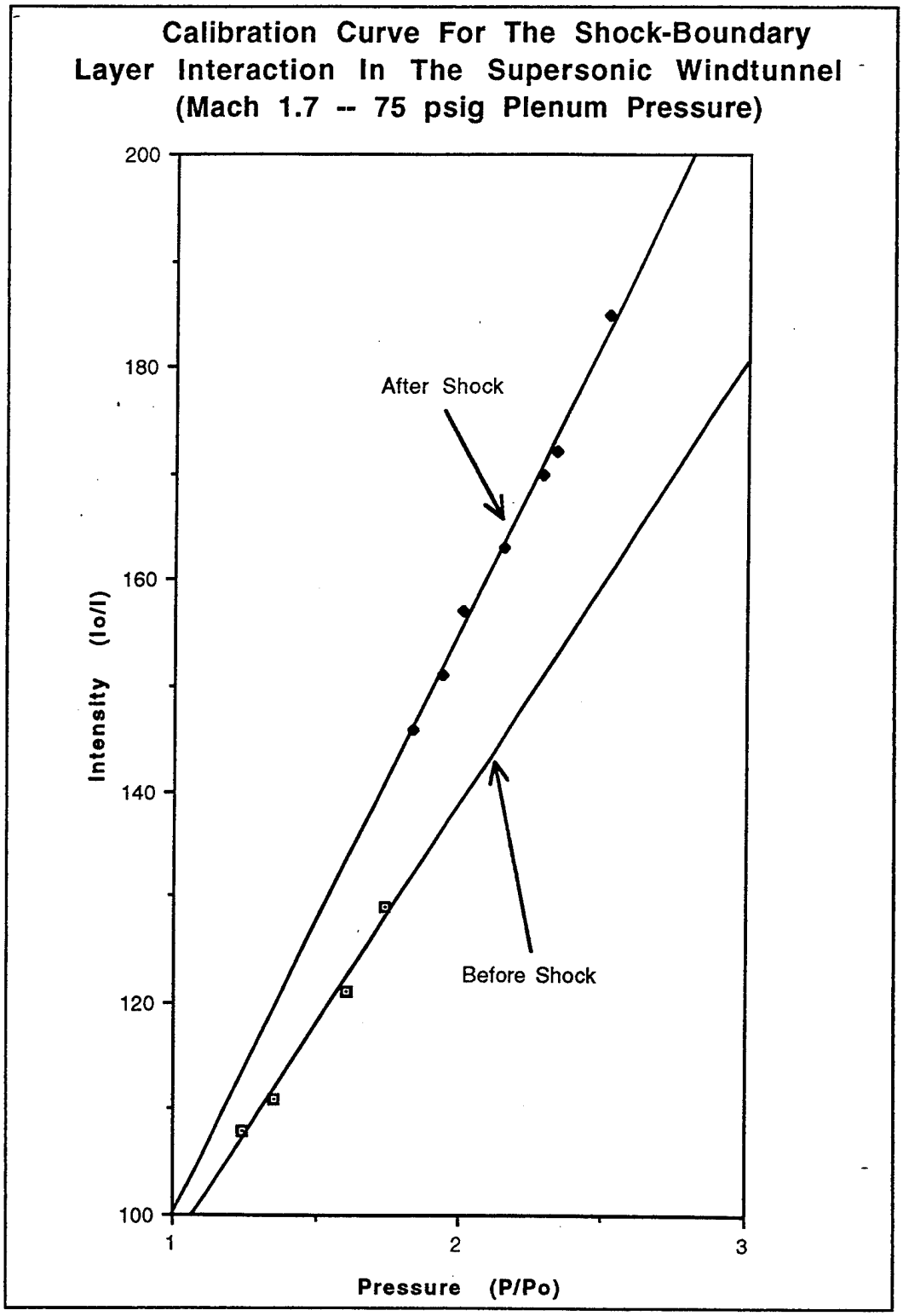


Figure 59. Calibration Curve for the Mach 1.7 Interaction

V. CONCLUSIONS AND RECOMMENDATIONS

The pressure-sensitive paint (PSP) technique offers a flexible and convenient method for measuring surface static pressures in aerodynamic testing. Its most significant feature is the non-intrusive manner in which it provides a mapping of a continuous pressure field over a surface. Because of its detailed spatial resolution (when compared to conventional pressure taps), a complete picture of the events occurring on the surface is available, including details not necessarily anticipated prior to testing. It appears to be highly suitable as a technique to use to validate results calculated using computational fluid dynamics (CFD). In the present study, pressure-sensitive paint was applied successfully in two experimental configurations involving shock-boundary layer interaction. The conclusions drawn from the present application are relevant to any first-time application of the technique.

The luminescent technique, although conceptionally simple, required learning. It was important to understand the entire process, including each of the components comprising the pressure measurement system (paint, optics, camera, software), the limitations of the system (particularly of the luminescent paint), and the interpretation of the measurements through calibration, before meaningful data were acquired. Several attempts to progress through the entire process were found to be necessary. Thus, the initial experimental arrangement (a flat plate immersed in an underexpanded jet) served well as a test bed for building experience before more complicated experimental geometries were attempted.

The components that comprised the current measurement system were adequate for initial experience, system development, and measurements. However, in order to make highly quantitative measurements routinely, some refinements are recommended. The camera and the digitizer combination are, by far, the most critical components in the PSP measurement system. The accuracy and precision of the measurements is highly dependent upon the dynamic range and signal-to-noise ratio of these components. The camera and digitizer used had a grey-scale resolution of eight bits giving a dynamic range of 256:1. Since many measurements, such as in shock-boundary layer interaction experiments, may generate changes in the luminescent intensity as little as two percent, it is crucial that the camera and digitizer be sensitive enough to these changes and to assign a gray-scale value that is appropriate for the given intensity level. Recommendations from NASA Ames Research Center and McDonnell Douglas have suggested a minimum of 14 bits for gray level resolution.

With a relatively low signal being detected, the signal-to-noise ratio at high light levels is limited by the photon shot noise. The accuracy of measurement is contingent upon the highest possible full-well potential of the CCD element, which requires a minimum generation of dark current. Active cooling of the CCD array would maximize the signal-to-noise ratio of the array. Such developments in CCD cameras can be expected [For example, Princeton Instruments Inc. currently offers a Penta Max camera that uses air circulation to cool its CCD array, which achieves -45 degrees Celsius]. Similarly,

system noise can be reduced by combining the digitizer with the camera, thereby reducing electrical noise, and then feeding the signal directly into a memory buffer in the computer.

The EPIX 4Meg Model 12 frame grabber and memory buffer and its associated software was limited in data collection. Since the board was limited to capturing only 11 images per sequence (assuming maximum resolution), the acquisition of one hundred images was far to slow to avoid inaccuracy of the results due to photodegradation of the paint. The EPIX 48Meg Model 12 frame grabber, for example, would provide the ability to capture up to 132 images per sequence. Not only would this reduce or eliminate the error associated with photodegradation, but image processing time would be significantly reduced. Data acquisition speed is mandatory in experiments in which the flow is not completely steady.

A similar issue concerns the present image-processing software. Designed for general applications, it is not the most efficient, or the most suitable, for the PSP applications. Although single-function algorithms such as registration software to spatially align two images together, to compensate for temperature sensitivity and apply the calibration to the data, and routines to pseudo-color the results must be written, consideration should be given to automating the entire process, from acquisition of the data to production of the calibrated pressure field map.

The temperature sensitivity of the paint and its effect on the results is a major concern if pressure measurements are to be made in the compressible flow regime. To accurately measure the pressures on a surface, it will be necessary to know the surface distribution of

temperature so that the calibration curves can be adjusted accordingly. Although temperature measurements could be made using thermocouples, this approach raises the same issues as those associated with using pressure taps to make pressure measurements. A possible solution is to use, concurrently, a high-performance infrared camera to record a high-resolution, continuous image of the temperature distribution on the surface. Since the results from infra-red cameras are produced using a digital process similar to that used in PSP, it is possible that the techniques could be combined to produce a temperature-compensated pressure map.

Finally, the applicability of the present technique to more complicated model configurations with more limited optical accessibility of the surface of interest, has yet to be attempted here. The combination of curved surfaces with significant temperature variations, and with limited optical access, will provide a significant challenge to the successful quantitative use of PSP.

APPENDIX A. RUSSELL-SANDERS COUPLING

Associated with the angular momentum of an electron is a magnetic moment. When the electron is placed in a magnetic field, the interaction of the field with the magnetic moment of the electron causes the angular-momentum vector to precess about the direction of the external field, much the same way a toy top precesses in a gravitational field. However, in contrast to the top, which can have an infinite number of momentum-vector orientations with respect to the field direction, the angular-momentum vectors of the electrons in an atom (or molecule) are allowed only certain orientations. The solutions of the Shrödinger equation dictate permitted orientations; not every orientation is allowed. The only allowed directions are those at which the components of the angular momentum along the direction defined by the magnetic field have certain quantized values. This behavior is called *space quantization.* [Ref. 10:p. 491]

Each orientation of the momentum vector with respect to the external field direction corresponds to a unique energy state. Since the angular motion of the electron is equivalent to an electromagnet, the energy of the interaction between the magnetic moment it possess and an external field can be expressed as $E = \mu H \cos \theta$, where H is the strength of the external field, θ is the angle between the field and momentum vector, and μ is the magnetic moment. [Ref. 26:p. 25]

Now consider what happens when a single unpaired electron is not in the presence of a magnetic field. Here, the orbital angular momentum of the electron creates the magnetic

field, defining a specific direction in space. Thus the angular momentum associated with the intrinsic spin of the electron is oriented with respect to this magnetic field. According to space quantization principles, the spin angular-momentum vector of the electron can have two orientations with respect to the direction defined by the magnetic field; this corresponds to the doublet line structure observed for the spectra of an atom, and is the basis for the spin quantum number (+1/2 and -1/2) assigned to the electron. [Ref. 26:p.27]

In an atom with several electrons, the orbits are usually oriented first with respect to each other, giving a resultant orbital magnetic moment. Similarly, there is a resultant spin moment which is oriented with respect to the resultant magnetic field due to the orbital motion. With space quantization, the resultant spin vector may have several orientations, each corresponding to a different energy level. Thus, the atom (or molecule) may have several energy levels for a single configuration. [Ref. 27:p. 79] These multiple energy levels for a single configuration of an atom (or molecule) is the basis for Russell-Sanders coupling which impacts the multiplicity of state that an atom or molecule can possess.

APPENDIX B. LUMINESCENCE COATING CHARACTERISTICS

The luminescent coating used in the present work possessed several undesirable characteristics of which the user must be aware if accurate results are to be obtained. A summary of these is presented below. For a more in-depth discussion, the reader may refer to the references mentioned.

A. TEMPERATURE SENSITIVITY

The photoluminescence process is temperature sensitive by nature. The coating used in the present work exhibited a non-linear response, and intensity decreased with increasing temperature. This response at a constant pressure is shown graphically in Figure B1. [Ref. 1:p36] The temperature dependence has a significant effect on the calibration curves of intensity vs. pressure. As is shown in Figure B2a, the variations in slope can be significant [Ref. 1:p. 62].

An interesting property displayed by the calibration curve for the coating is the condition where the coating-sensitivity coefficients add to unity (i.e. $A + B = 1$, in the Stern-Volmer equation). This occurs when the data taken for I and I_o are taken at the same temperature. If this is not the case, the coefficients add to other than one, $A + B \neq 1$. The consequences are illustrated in Figure B2. In Figure B2(a) only the 23.7 ° C curve exhibits the property that $A + B = 1$ while the 50 and 6 °C calibration curves were calculated with I and I_o at different temperatures. In Figure B2(b), the 50 and 6° C

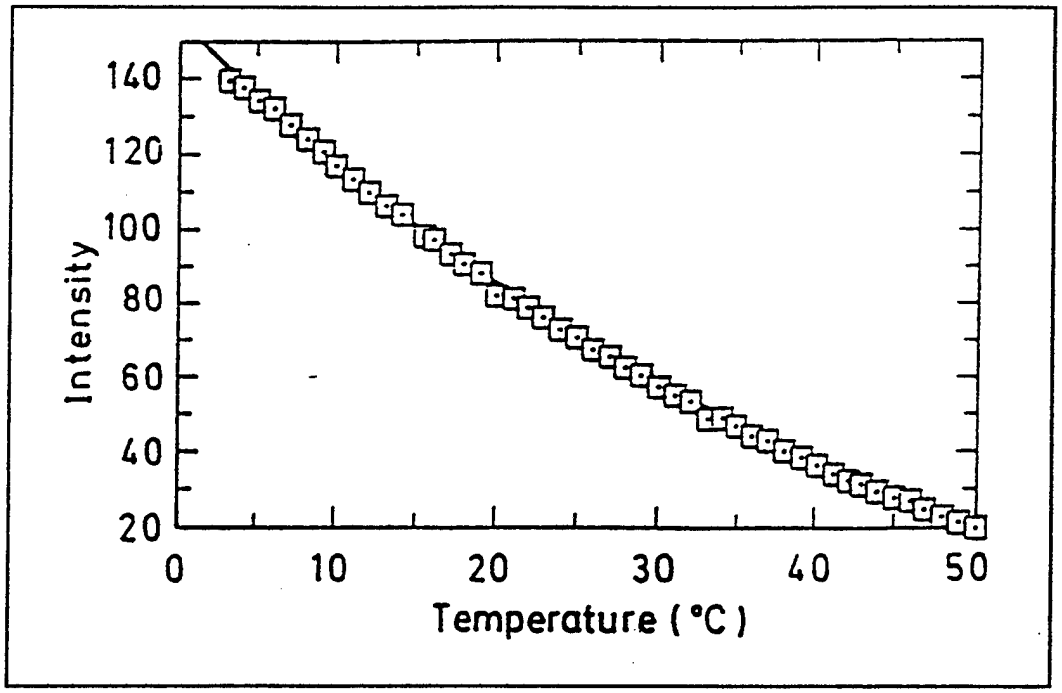


Figure B1. Luminescence Intensity as a Function of Temperature [From Ref. 1:p. 36]

calibration curves have been replotted using data for both I and I_o obtained at similar temperatures. Clearly, the slope and zero intercept have been significantly altered. [Ref. 1:p.37]

B. PHOTODEGRADATION

When subjected to ultraviolet light, the luminescent coating undergoes photodegradation, resulting in a decrease of its response with time of exposure. A representative example of this is shown in Figure B3 where intensity is plotted as a function of time of exposure. In this case the coating lost 46% of its response after one hour of exposure. [Ref. 1:p. 36]

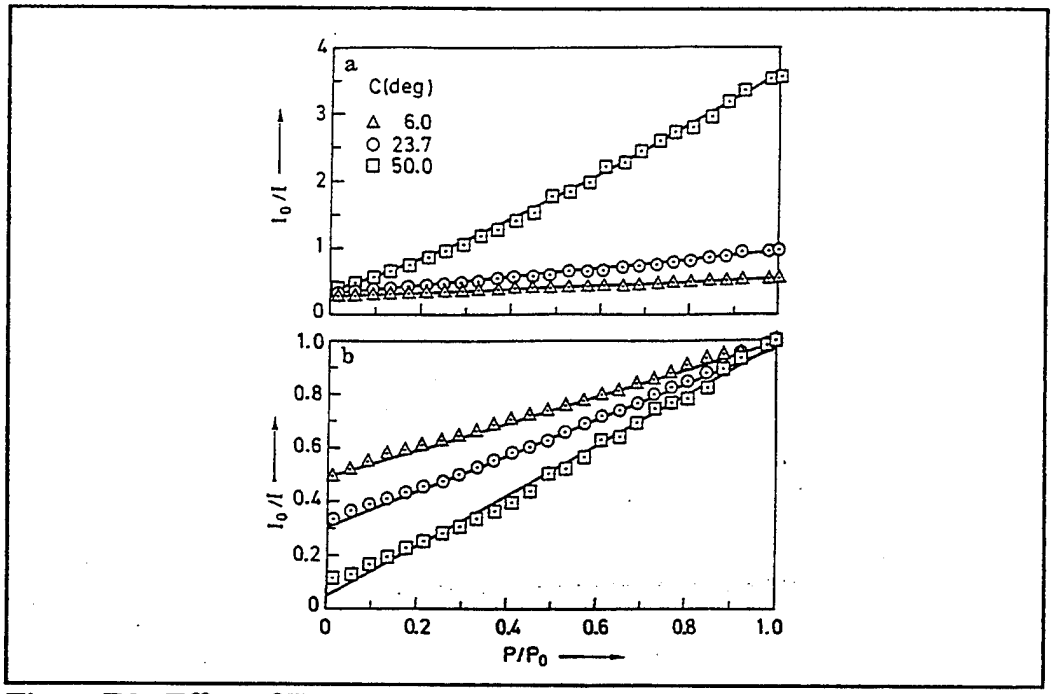


Figure B2. Effect of Temperature on Coating Calibration Curves [From Ref. 1p: 37]
(a). I_o for Curve Measured at 23.7° C
(b). I_o for Curve Taken at its Respective Temperature

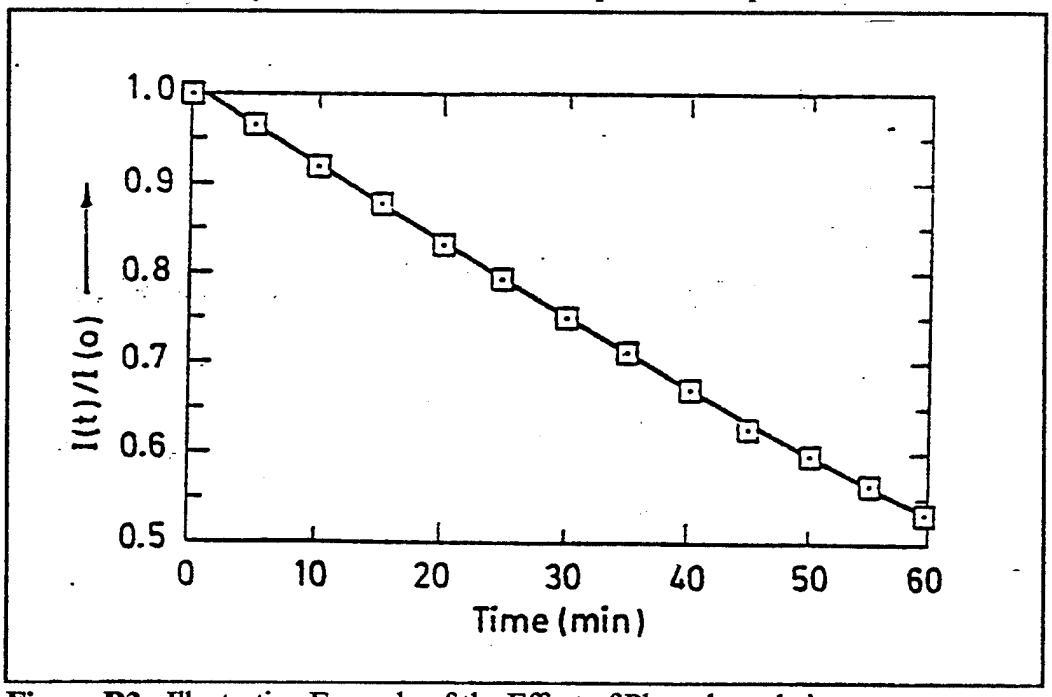


Figure B3. Illustrative Example of the Effect of Photodegradation on Response Time [From Ref. 1p:36]

C. TIME RESPONSE

The luminescent coating used in the present work has been found to exhibit a time response on the order of 1 second limiting measurements of pressure fluctuations to no greater than 1 Hz. [Ref. 8:p. 3]

This limitation is not a characteristic of the active molecule. In theory, the time response of the coating to pressure transients may be as fast as the decay of luminescence. For platinum octaethylporphyrin this is approximately 0.1 milliseconds. The problem lies with the polymer matrix in which the active molecule is embedded. By limiting the rate of oxygen diffusion, the polymer slows the optical response to surface pressure fluctuations. [Ref. 1:p. 41]

D. COATING THICKNESS / INDUCTION PERIOD

Kavandi [Ref. 9:p.86] has conducted tests to determine if film thickness has any effect on calibration results. Over the range of 5.5 micrometers to 17 micrometers, consistent with normal application, no significant variations were noted. However, a noticeable lag, or "induction period", existed between the time excitation light was turned on and the time that the detected luminescence reached maximum intensity. The period of maximum intensity was observed to be in the range of 30 to 45 seconds and it is therefore advisable to allow this period to elasped before taking data. A graph of absolute intensity as a function of time following exposure to the exciting light is shown in Figure B4. [Ref. 9:p.89]

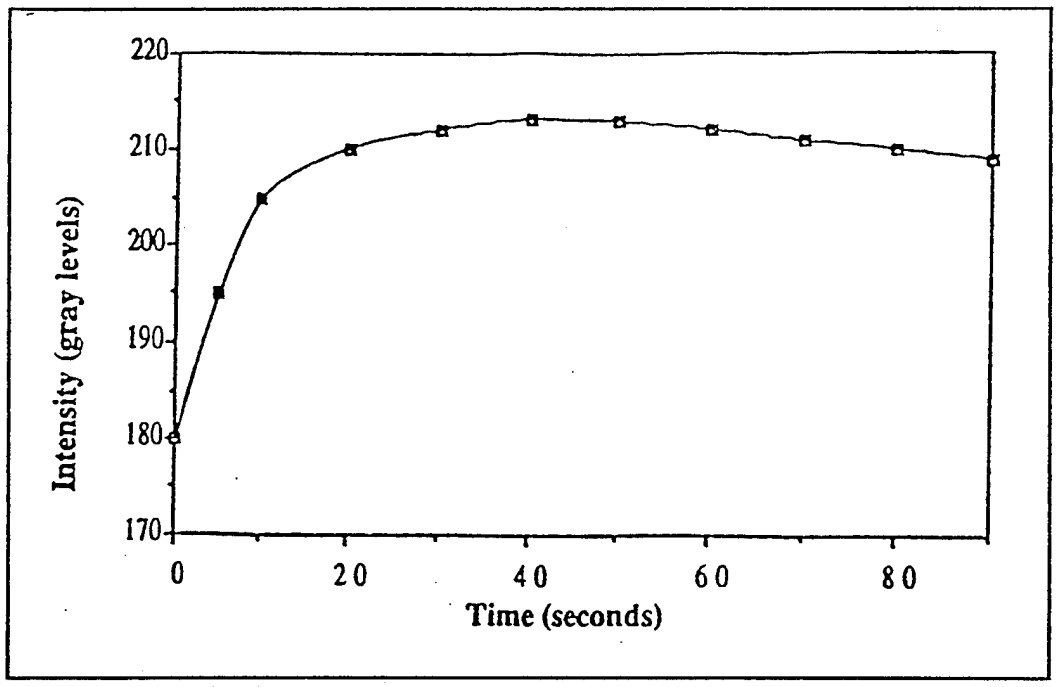


Figure B4. Induction Period of the Luminescent Coating with Thicknesses in Excess of 17 Micrometers [From Ref. 9:p. 89]

APPENDIX C. EPIX SOFTWARE SUMMARY

This appendix outlines the software steps used in acquiring, processing and reducing image data. All information discussed here may be found in [Ref. 23]. The appendix is intended to serve as a user guide but is not meant to be a substitute for the EPIX user's manual. The user's manual is vital to developing a sound understanding of the software in order to be able to use it to its fullest extent. The data acquisition and image processing system is set up such that the menus and commands are displayed on the computer monitor while the images are displayed on the Sony image monitor.

A. IMAGE DATA ACQUISITION

The main menu for the EPIX 4MIP-4MIPTOOL software is shown in Figure C1. Prior to data collection, the video resolution is set. Selecting "Video Resolution" from the main menu, the video resolution sub-menu will be displayed as in Figure C2. Check to insure that the "Interlace: Use Distinct (2) Fields ?" is set to "ON". The sampling resolution is considered next and it is application dependent. The sampling resolution sets the size of the video window displayed on the image monitor, allowing the selection of a smaller field of view. The maximum resolution is 752 pixels per line by 480 lines per frame or image (Two fields make up one frame; however the number of lines selected is based on each field, the maximum number being 240. For both fields to be active, the interlace function must be on). Upon setting the desired sampling resolution, the

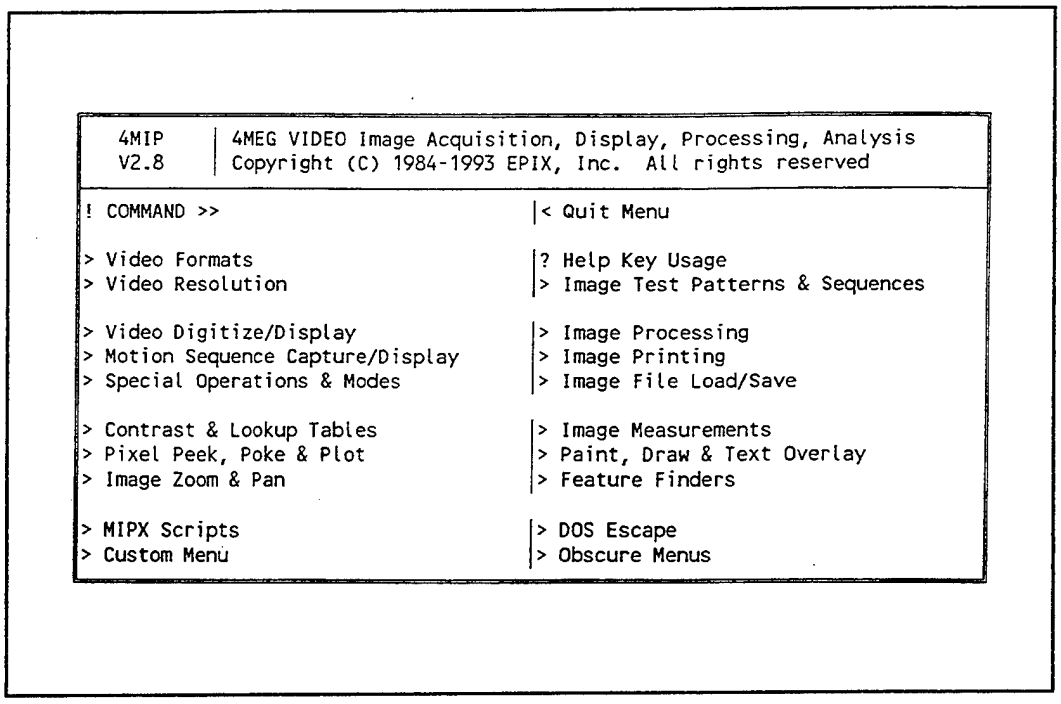


Figure C1. "Main Menu" for EPIX Interactive Image Analysis Software

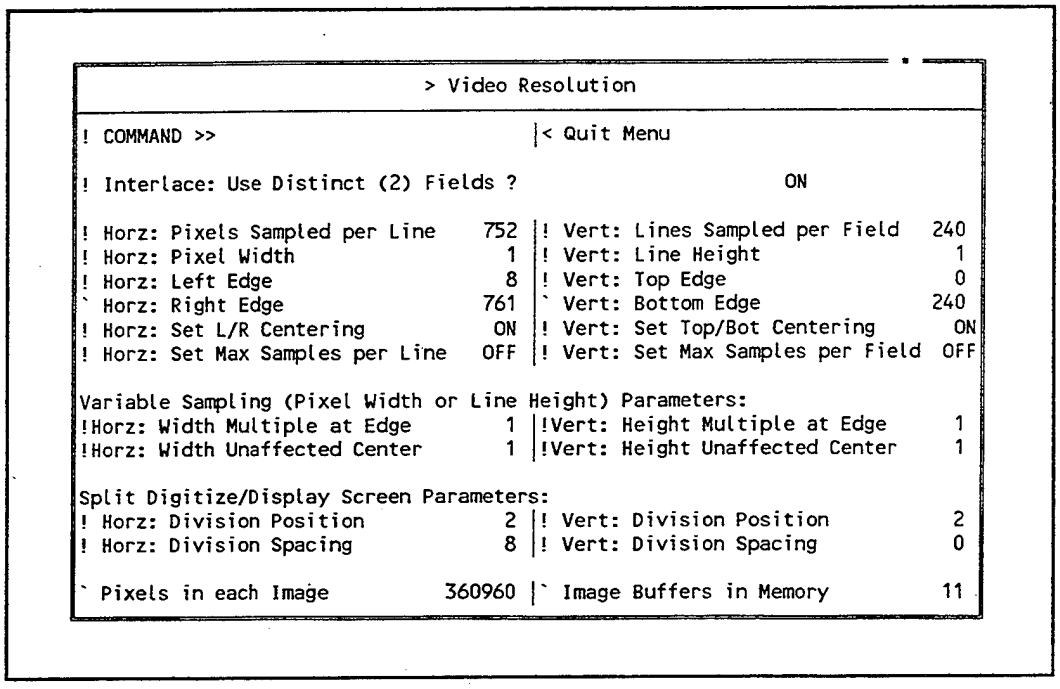


Figure C2. "Video Resolution" Sub-Menu

number of frame buffers available for capturing images is displayed in the lower right corner of the menu. For 752 x 480 resolution, 11 frame buffers are available. After setting the resolution, return to the main menu by selecting "Quit Menu".

From the main menu, select the "Video Digitize/Display"; this menu is shown in Figure C3. Select the function "Digitize", the result of which is a real-time video display of the camera's field of view. Adjustments to the camera can be performed, such as focus, gain, iris setting, etc., to achieve the desired image. When complete, return to the main menu; the real-time image will remain displayed on the monitor.

Next select the "Motion Sequence Capture/Display" sub-menu; this menu is illustrated in Figure C4. The first step here is to choose the length of the sequence, and which buffers are to be used, by selecting the sequence starting and ending buffers. For example,

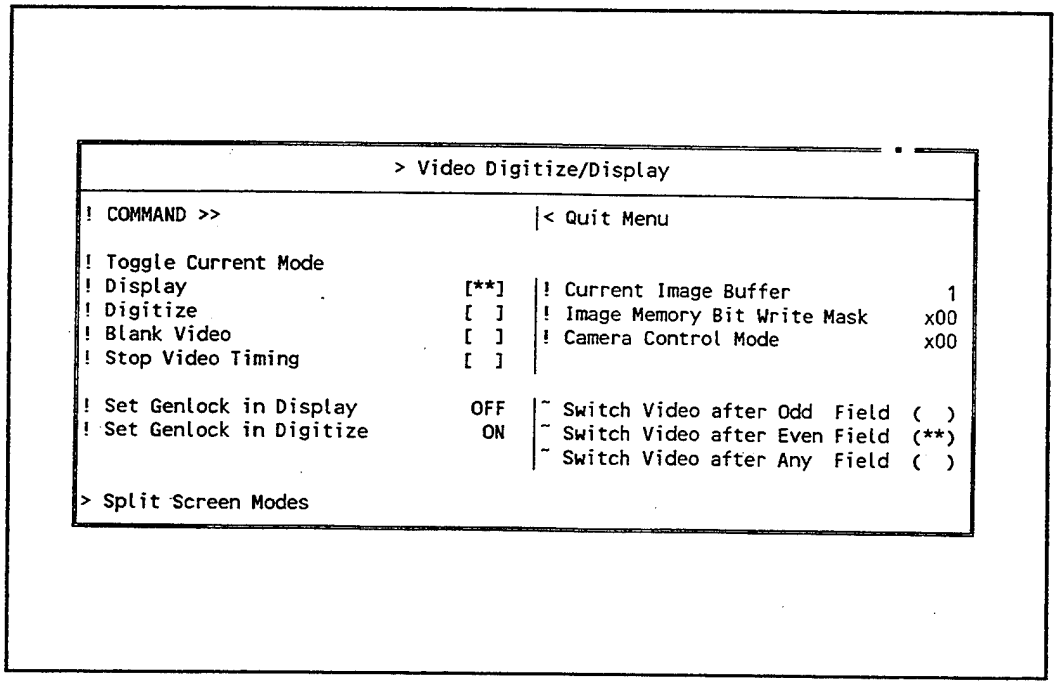


Figure C3. "Video Digitize/Display" Menu

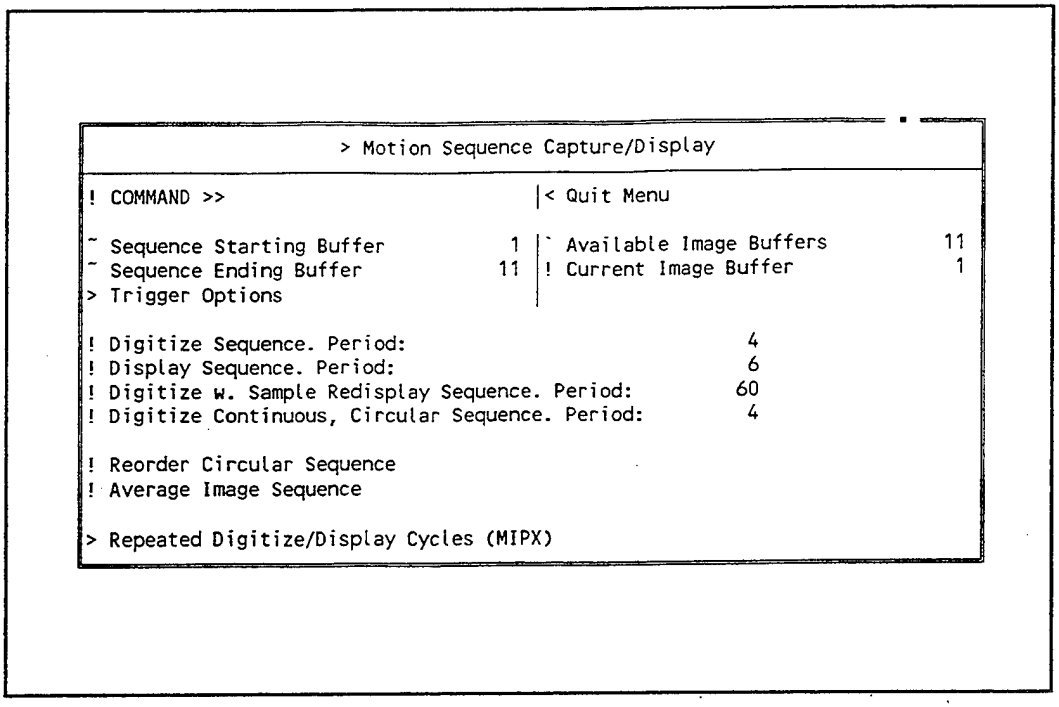


Figure C4. "Motion Sequence Capture/Display" Sub-Menu.

in the flat plate/jet interaction work only 10 of the 11 buffers were used; thus the starting buffer was set to 1 and the ending buffer to 10.

The time interval between consecutive samples is then set with the "Digitize Sequence. Period:" function. The period is based on units of video fields if the video is not interlaced (1/60 sec) or video frames if the video is interlaced (1/30 sec). The COHU camera was set internally to send an interlaced image to the frame-grabber board. Since the incoming signal to the board is interlaced, the software can be programmed using the interlace function to store either an image with both fields of the image (interlaced) or an image with a single field (non-interlaced). With the "Interlace: Use Distinct (2) Fields ?" set to active, the period will be based on units of frames. For the jet/plate interaction experiment collection, the period was set to the default value of 4 frame periods between each

captured image or 4/30 = 2/15 of a second between each captured image. For the supersonic wind tunnel experiment the period was set to 1 or 1/30 of a second between each captured image.

One note concerning this function; to enter the desired period, the mouse or arrow keys are first used to position the cursor on the function. The period is entered using the numeric keys, the program responding to the entry by "highlighting" it red. The entry is then entered into memory by either strobing the left mouse button or striking the "enter" key. This action, however, also starts the execution of the algorithm for sequence image capture. When complete, all designated buffers will contain a captured image. If the image buffer used to display the real-time image lies between the starting and ending sequence buffers, it too will contain a captured image. Therefore, until the desired event is being displayed on the monitor in the real-time format, the entry for the period should not be strobed or the above sequence of events will have to be repeated to redisplay the real time image. It is, of course, not necessary to display a real-time image to capture a sequence of images. By simply re-strobing the "Digitize Sequence. Period:" a new set of images is stored in the designated buffers. Displaying a real-time image of the desired event on the monitor is simply a matter of choice.

B. IMAGE PROCESSING

1. Averaging

The procedure outlined in Chapter III for data collection of the wind-on, wind-off, and dark-current conditions involved executing the above-described steps ten times, i.e., ten images per sequence, executing the motion-sequence algorithm ten times, for a total of one hundred images. After each sequence run, the images in the designated buffers were averaged together to form a single image. This was done by strobing the function "Average Image Sequence" in the "Motion Sequence Capture/Display" sub-menu. The averaged image is stored in the buffer designated as the starting sequence buffer.

The hard drive of the 80386 PC used in the present work contained software applications used in other research, which presented inadequate memory space for image-data storage. Therefore, all data was transferred from the frame-grabber board to floppy disk. The command to store data to disk is found in the main menu and is designated as "Image File Load/Save". From the resulting sub-menu, select the option "File Load/Save, Tiff Format w. AOI". The sub-menu for this option is brought up onto the computer screen. Position the cursor on the option, "Save Image to File. Name", and type "b: filename.tif". Striking the "enter" key will bring up the menu "Select IMAGE BUFFER and/or AREA OF INTEREST" to appear; select the option "Image Area Of Interest: Full Image". The image will then be sent to the floppy. "Full Image" refers to the image size that is set in the "Video Resolution" sub-menu; thus if the image resolution is set to 752 x 480, this will be the image size that is stored on the disk.

Once ten averaged images have been saved to disk, they can be loaded back into ten frame buffers on the frame-grabber board using "Image File Load/Save" function. Again, select "File Load/Save, Tiff Format w. AOI" and then position the cursor on "Load Image from File . Name:". Type "b:filename.tif" and strike "enter". In the "Select IMAGE BUFFER and/or AREA OF INTEREST" sub-menu, select "Image Area Of Interest: Full Image" and strike "enter". The image will be loaded into the current image buffer. The current image buffer is selected by simply toggling the Pg Up/Pg Dn keys.

With all ten averaged images loaded into the frame grabber, return to the main menu and select the "Motion Sequence Capture/Display" function. Insure the "Sequence Starting and Ending Buffers" reflect the sequence of buffers that the averaged images are stored in (See Figure C4). This complete, the images are averaged together using the "Average Image Sequence" option, the resultant image being stored in the buffer designated the sequence-starting buffer. This image represents either the wind-on and wind-off images that will eventually be ratioed or the averaged dark-current image that must first be subtracted from these two images. The three resultant images are again stored on floppy disk.

2. Subtraction

The averaged wind-on, wind-off, and dark-current images are loaded back into consecutive buffers of the frame-grabber board using the steps for loading files that were discussed above. From the main menu select "Image Processing", from which the image-processing sub-menu is displayed on the screen as in Figure C5. Choose the "Two Image

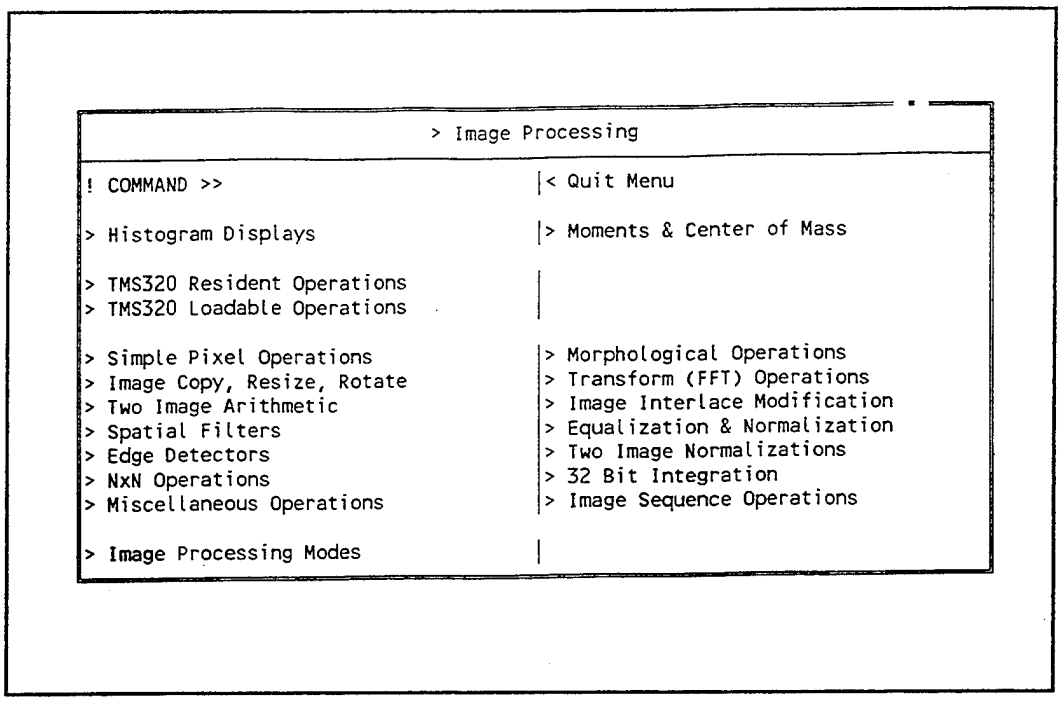


Figure C5. "Image Processing" Sub-Menu

Arithmetic" option, which sub-sequently displays the options available for conducting operations involving two images, this menu being illustrated in Figure C6. Four subtraction options may be selected; the option "Abs(PixB - PixA)" was used in the present work, where the absolute value of an intensity value is taken if it is less than zero. When this function is selected, the "Select IMAGE BUFFER and/or AREA OF INTEREST" for PixA menu is displayed. Before selecting anything from this sub-menu, ensure that the current-image buffer that is being displayed on the image monitor is that containing the dark current image; this represents PixA. From the "Select IMAGE BUFFER and/or AREA OF INTEREST" menu, choose the option "Full Area of Interest: Full Image". When this step has been completed, the "Select IMAGE BUFFER and/or AREA OF INTEREST" for PixB is displayed. Here, ensure the current image buffer

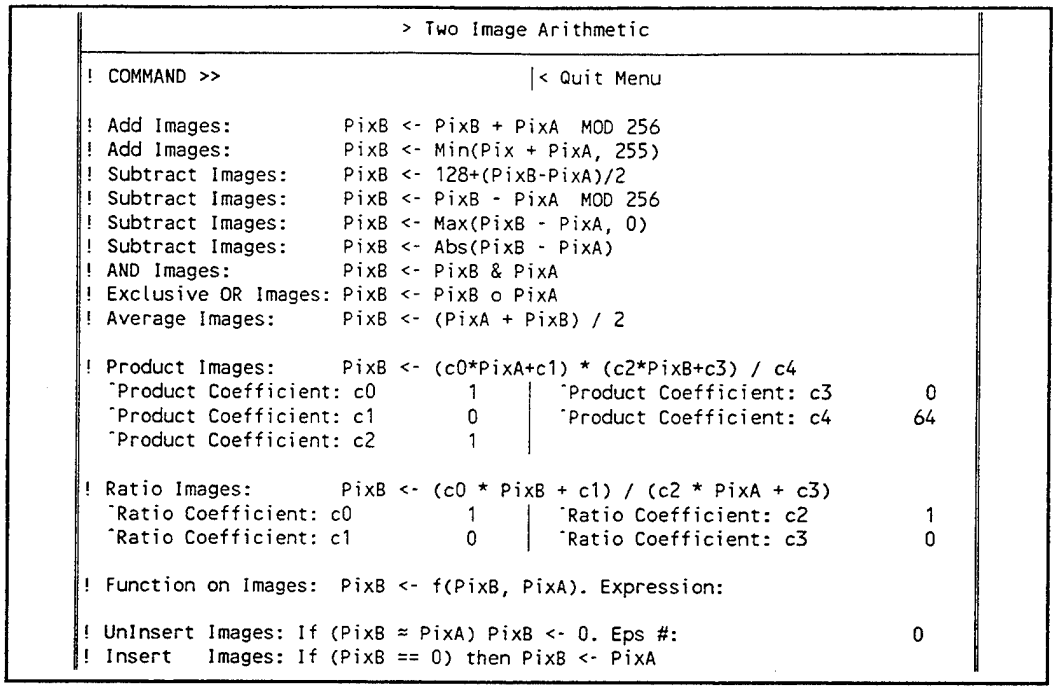


Figure C6. "Two-Image Arithmetic" Sub-Menu

being displayed on the monitor is either the wind-on or wind-off image; this represents PixB. Again select "Full Area of Interest: Full Image" from the sub-menu. Execution will begin, the modified image residing in the frame buffer that originally contained PixB. Conduct this operation on both the wind-on and the wind-off images.

3. Registration

Registration of images will be unique to every application. As discussed in Chapter III, the registration procedure between the wind-on and wind-off images for the jet/flat plate interaction involved solid body motion, a relatively simple registration problem. Registration between images that involve more complex scenarios such as translational shifts, rotational shifts, and geometric distortions, will require more complicated software procedures than were used here.

If the extent of distortion between the images is simply solid body translation, then the following procedure can be used: Load the wind-on and wind-off images into consecutive buffers. From the main menu, select the "Pixel Peek, Poke & Plot" option; this sub-menu is shown in Figure C7. When this menu is displayed, the cursor will be overlaid on the image monitor, and can be controlled with the left button on the mouse is depressed. The cursor coordinates remain the same as the image buffer is changed, allowing examination of feature registration among image sequences. Thus using the wind-off image as the reference image, the vertical and horizontal characters of the cursor are aligned on a feature or control point that is distinctive in both images. By shifting back and forth between the buffers containing the images, using the Pg Up/Pg Dn keys and not disturbing the cursor location, an indication of the magnitude of distortion is obtained.

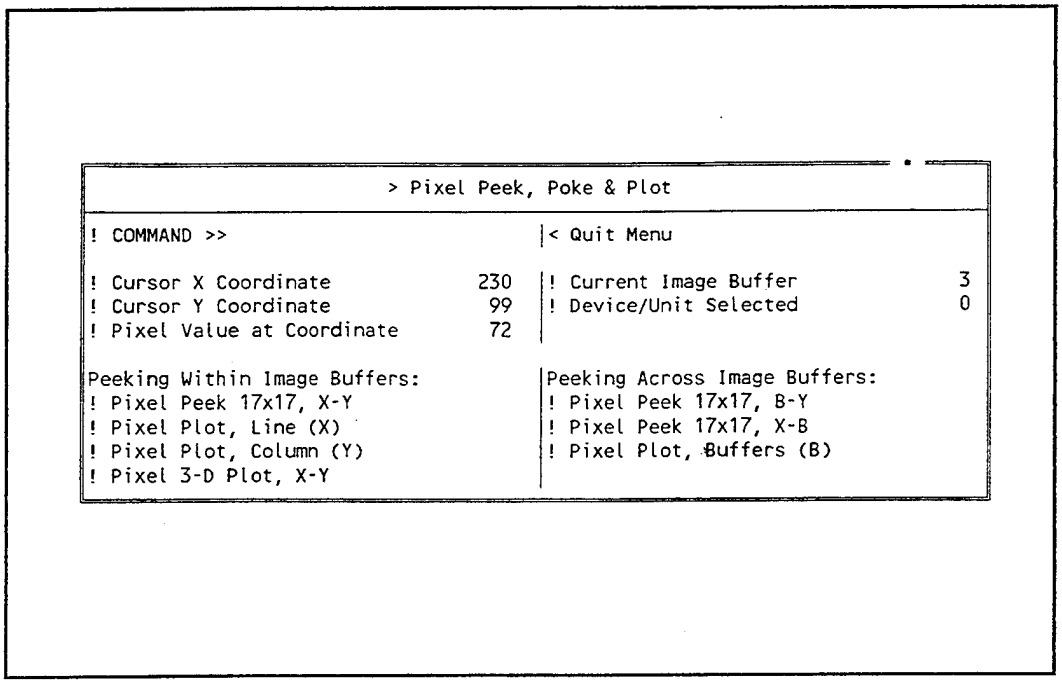


Figure C7. "Pixel Peek, Poke and Plot" Sub-Menu

Return to the main menu and select "Image Processing", followed by the option "Image Copy, Resize, Rotate"; this sub-menu is shown in Figure C8. The function "Copy & X,Y Shift" copies an image , shifting the image left or right and up or down in its buffer. The *Left(-X) Right(+X) Shift* parameter specifies the number of pixels the image is to be shifted left or right; the *Up(-Y) Down(+Y) Shift* parameter specifies the number of pixels the image is to be shifted up or down. When the parameters have been entered, strobe the "Copy & X,Y Shift" function using the left button of the mouse or the "enter" key. (Ensure that the wind-on image is in the current image buffer prior to this step). The "Select IMAGE BUFFER and/or AREA OF INTEREST" for image A menu will appear from which the "Image Area of Interest: Full Image" option is selected; when this is done the "Select IMAGE BUFFER and/or AREA OF INTEREST" will re-appear for image B

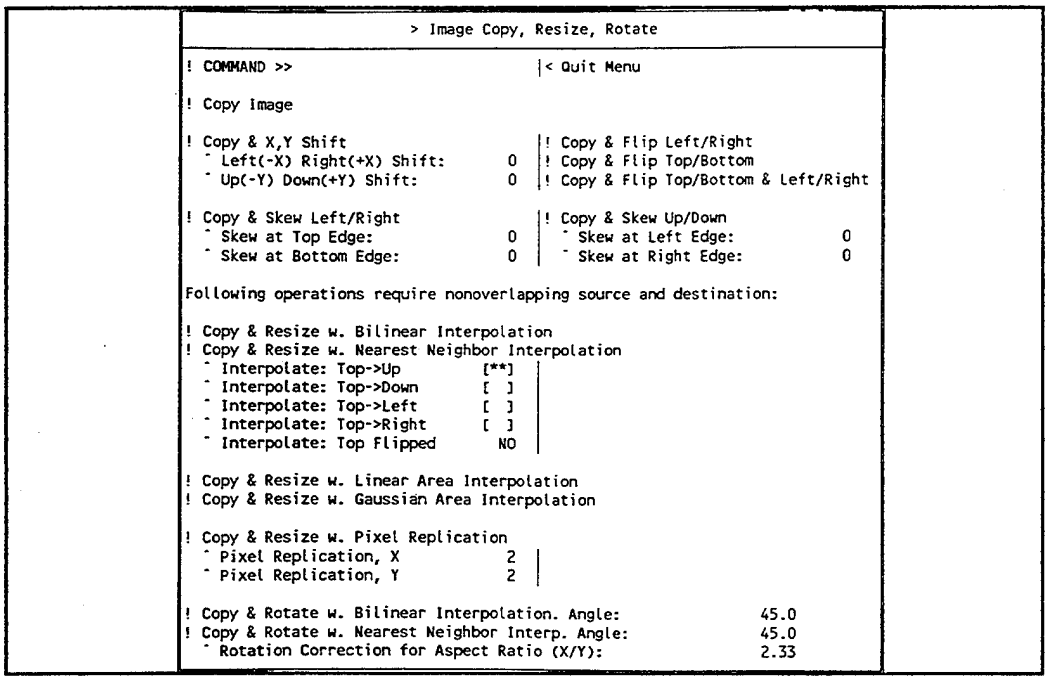


Figure C8. "Image, Copy, Resize, Rotate" Sub-Menu

where again the option "Image Area of Interest: Full Image" is chosen. When this selection is made the operation will then be executed. The current image buffer containing the wind-on image will be replaced with the modified wind-on image. Return to the "Pixel Peek, Poke & Plot" sub-menu and use the cursor to determine if the wind-on and wind-off images are properly registered. Several iterations may be necessary until the images are aligned.

4. Ratioing

With the images correctly registered, the ratioing process can now be executed, i.e., the wind-off may be divided by the wind-on images. Proceed to the "Two Image Arithmetic" sub-menu as previously done when the dark current image was subtracted from the wind-on and wind-off images. Under the "Ratio Images" option, set the ratio coefficients, that are used for "gain and offset", as follows: c0 = 100 (or 128), c1 = 0, c2 = 1, c3 = 0. Next strobe the "Ratio Images" function which will cause the "Select IMAGE BUFFER and/or AREA OF INTEREST" menu for PixA to be displayed. Ensure the current image buffer is displaying the wind-on image. Select "Image Area of Interest: Full Image". This will cause the "Select IMAGE BUFFER and/or AREA OF INTEREST" to be re-displayed for PixB. Now shift the buffer containing the wind-off image such that it becomes the current image buffer. Again select "Image Area of Interest: Full Image". The ratioing process will then commence replacing the image designated as PixB, i.e., the wind-off image, with the modified image.

5. Thresholding

A black background is usually added to the ratioed image to provide contrast and enhancement to the resultant image. From the main menu chose "Image Processing" and then the option "Simple Pixel Operations". Under the function "Threshold Pixel Values" set the values as follows:

- Threshold: Lowbound 0

- Threshold: Highbound 255

- Threshold: NewValue 0

Strobe the "Threshold Pixel Values" function with the left mouse button; the "Select IMAGE BUFFER and/or AREA OF INTEREST" menu will appear. The boundary shape of the painted surface depicted in the ratioed image will dictate which area of interest to select for this image processing operation, i.e., "Interactive Rectangular", "Interactive Elliptical", "Interactive Freehand", and "Interactive Polygon". The area of interest includes the area of the image that the painted surface does not occupy; for the flat plate, since the sides were parallel to the image axis, the "Interactive Rectangular Region" was selected as the region of interest. The area of the flat plate image not occupied by the plate was broken down to four areas of interest, that is, the area above the plate, below the plate, left of the plate, and to the right of the plate. Using the mouse with the right button depressed, these areas were outlined individually with the cursor. Once the areas had been outlined, the thresholding process was executed.

6. Pseudocoloring

To add false coloring or pseudocoloring to the gray-scale image, select the "Contrast & Lookup Tables" option from the main menu. This menu is illustrated in Figure C9. Each of the primary colors, red, green, and blue are set by selecting the "Numerically Set & Show" option for the individual colors. The option displays the sub-menu illustrated in Figure C10. Using the function "Set Partial Linear Ramp" any configuration of linear ramps may be constructed. A graphical display of the inputs can be shown on the computer screen by selecting the "Plot Table" option in the menu illustrated in Figure C10.

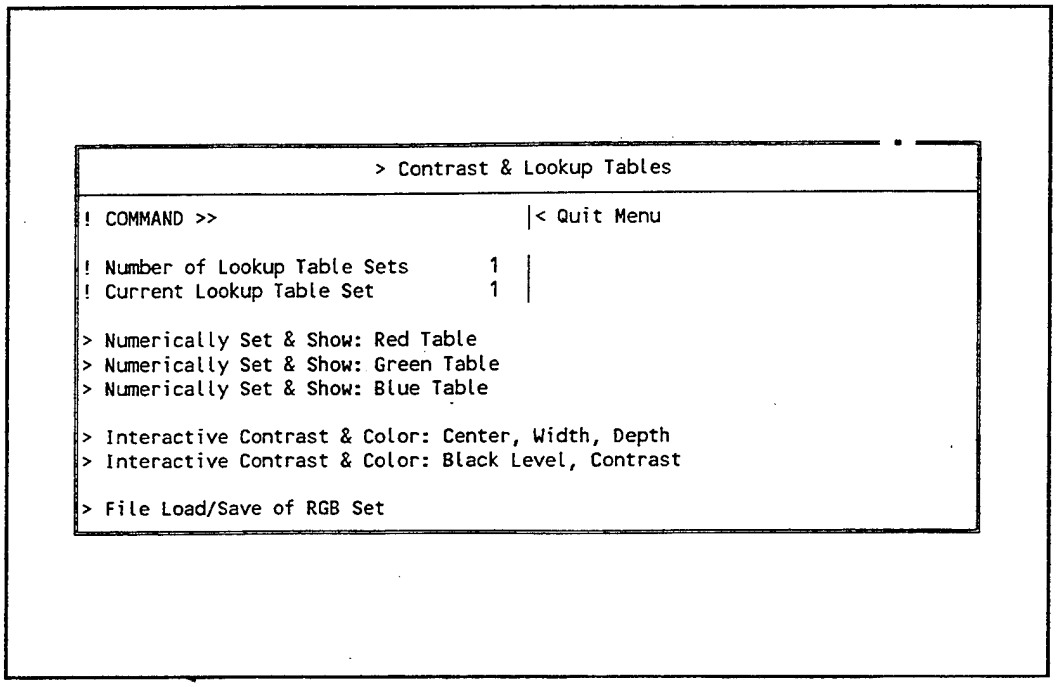


Figure C9. "Contrast & Lookup Table" Sub-Menu

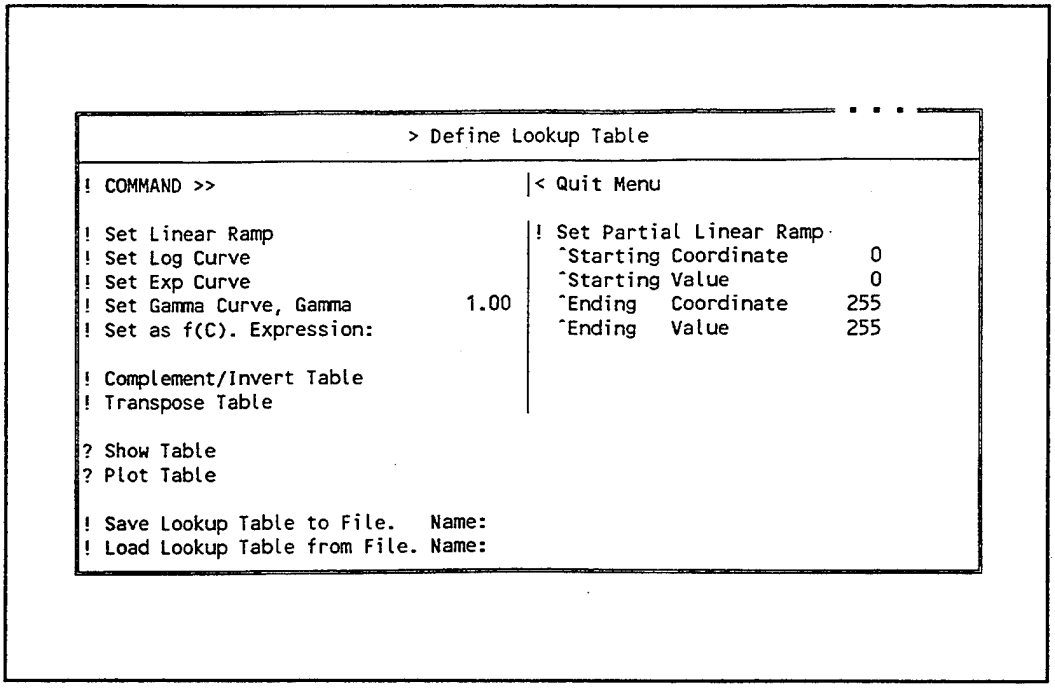


Figure C10. "Define Lookup Table" Sub-Menu

APPENDIX D. DARK CURRENT

Thermal generation of electrons or "dark-current" is a naturally-occurring consequence of using semiconductor devices for photo reception. To understand dark-current effects on pressure-sensitive paint measurements, it is necessary to review the operation of a charged-coupled device (CCD). A schematic illustration of a CCD is shown in Figure D1.

Consider a single CCD electrode in Figure D1. Absent the application of a bias to the gate electrode, a uniform distribution of holes or majority carriers exists in the p-type semiconductor. As a positive voltage is applied to the gate, the holes are repelled from the semiconductor immediately beneath the gate, forming a depletion layer or potential well. An increase in the voltage causes the depletion region to extend further down into the bulk semiconductor, causing an increasing positive potential known as a surface potential to exist at the semiconductor and insulator (oxide) interface. Eventually a gate bias is reached at which the surface potential becomes so positive that the minority carriers (in this case electrons) are attracted to the surface where they form an extremely thin but very dense inversion layer. [Ref. 28:p. 6]

In image-sensing applications of CCD's, the minority carriers are generated when photons entering the silicon substrate excite the valence electrons of the material into the "conduction band", becoming free electrons. The electrons are then collected under the

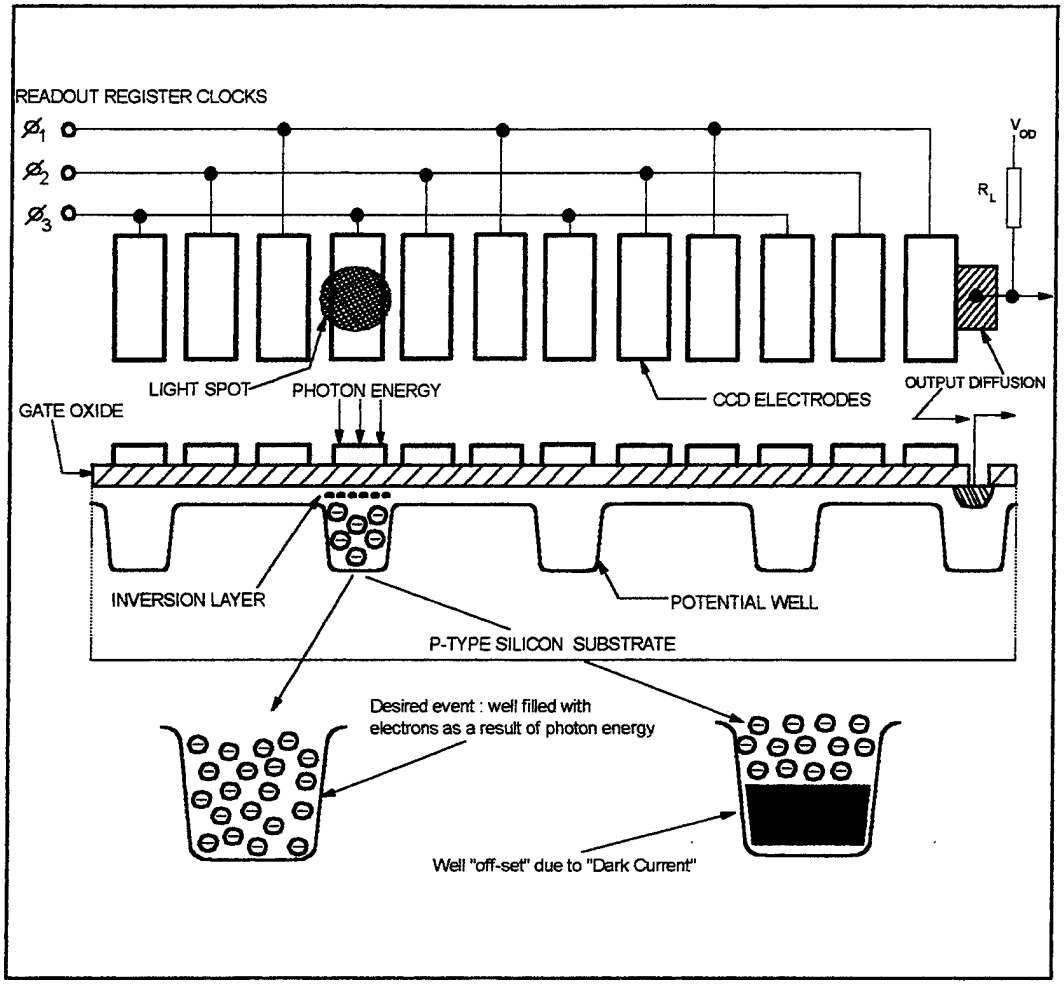


Figure D1. Representation of the Effect of Dark-Current on the Creation of Charge

electrode of the applied bias. The number of electrons under the electrode within a given period of time is proportional to the local light intensity.

In addition to the photoelectric effect described above, free electrons can also be produced by thermal energy, of which the rate of generation increases exponentially with temperature for a pure semiconductor. Thus, the presence of thermally generated minority carriers limits the maximum possible usefulness of the potential well by displacing optically generated carriers. This produces an "offset" in the measurement image such that the

zero-incident light level does not correspond to a zero gray-level pixel index. Thus, the dark image must be removed from the measurement images. To do this, a dark image is acquired by prohibiting any light from striking the CCD array and sampling an image. Several of these images are taken and time averaged together. This is necessary because dark current generation tends not to be uniform over a whole array. The resulting averaged dark current is then eliminated from the measurement images using image processing techniques discussed in Chapter III.

APPENDIX E. SUPERSONIC NOZZLE DESIGN PROGRAM

Software for the design of two-dimensional supersonic nozzles was acquired from the Naval Surface Warfare Center (NSWC), White Oak, Maryland. The software package is comprised of two programs; the first program is concerned with establishing the isentropic contour of the nozzle while the second corrects for the viscous effects of the fluid and adjusts the contour accordingly.

Support documentation for the software from a user's standpoint is not available. In addition, the early fortran code is not well structured, making it difficult to interpret the algorithm and follow its logic. It is difficult to recognize many of the variables, and there are no comment statements. However, enough information has been deduced such that the program may be operated effectively. The intention of this appendix is to document what is now known about the software.

Modifications have been made to the original software primarily involving the manner in which program input entries are made and data storage accomplished. Originally, the program was designed to access punch-card readers and magnetic-tape drives for data input and output management. Entries are now made directly to the program through interactive software in a format that is more flexible and user friendly. Output data are stored in a file structure compatible with hard drive systems. A listing of the modified software is given in Section C of Appendix E.

A. INVISCID CONTOUR SOFTWARE (Program char6)

The program "char6" generates the isentropic contour of the supersonic nozzle using the method of characteristics. Initiation of the program will depend on the filename assigned to the object code at the time of compiling and linking of the source code. Once started, the program first displays an introductory summary as shown in Figure E1. As indicated by these remarks, the storage of the output data is currently limited to the data for one run. A successive run will overwrite the data storage files from the previous run.

Entries made by the user through the interactive sequence of prompts for input data have been sub-divided into two categories; the first category identifies the "characteristic" lengths and nozzle type that will be used to define the configuration; the second specifies dimensions and flow characteristics to which the nozzle will be designed.

U.S. NAVAL ORDANCE LABORATORY, WHITE OAK, MARYLAND

COMPUTER PROGRAM FOR THE DESIGN OF TWO-DIMENSIONAL SUPERSONIC NOZZLES

PART I

THE ISENTROPIC CORE OF THE NOZZLE

INTRODUCTION:

This program uses the method of characteristics to determine the contour of a two-dimensional isentropic core of a supersonic nozzle. The program requires two sets of inputs; one that provides the general characteristic lengths and nozzle types that will be used to describe the nozzle; the second set outlines the specific flow characteristics and geometric lengths that the contour will be designed to. The program is currently limited to one output file; in other words successive runs will overwrite data generated on previous runs.

Figure E1. Illustrative Example of the Introductory Remarks for Program char6

1. Category 1: Characteristic Lengths and Nozzle Types

1. INPUT A DESCRIPTION OF THE PROJECT

Allows a short summary of the project to be recorded as part of the final output summary. The description is limited to 80 characters.

2. INDICATE TYPE OF NOZZLE, 1-SHORT, 2-REGULAR, 3-EXPONENTIAL

Provides the option of choosing a specific contour shape. The methodology the program uses to generate the contour begins by first determining the centerline Mach number distribution based on the choice of contour. The method of characteristics is then used in conjunction with the centerline distribution in determining contour geometry.

3. INDICATE THROAT OR EXIT HEIGHT TO BE READ, 1-EXIT, 2-THROAT

Irrespective which is used; the program calculates the option not selected using simple isentropic relations. Both heights are employed in the program in computing the contour.

4. INDICATE CHARACTERISTIC HORIZONTAL LENGTH TO BE READ, 1-EXIT LENGTH, 2-START OF TEST RHOMBUS

Refer to Figure E2 for clarification of the horizontal lengths discussed. The exit length is defined as the distance between the nozzle throat and the nozzle exit.

The characteristic network created by the method of characteristics is such that the last two characteristic lines in the grid complete the expansion process by turning the flow parallel to the centerline of the nozzle and thus expanding it to the desired test section Mach number. These two characteristic lines can also be thought of as forming half of an imaginary rhombus as shown in Figure E2. This is known as the test section rhombus. The distance between the nozzle throat and the intersection formed by the two characteristic lines defines the horizontal length referred to above.

5. INDICATE OUTPUT, 1-STEP-BY-STEP, 2-WALL POINTS ONLY

Generally, the approach used in applying the method of characteristics can be summarized in a three step process: Step 1 -- the determination of the characteristic lines in the *xy* space using

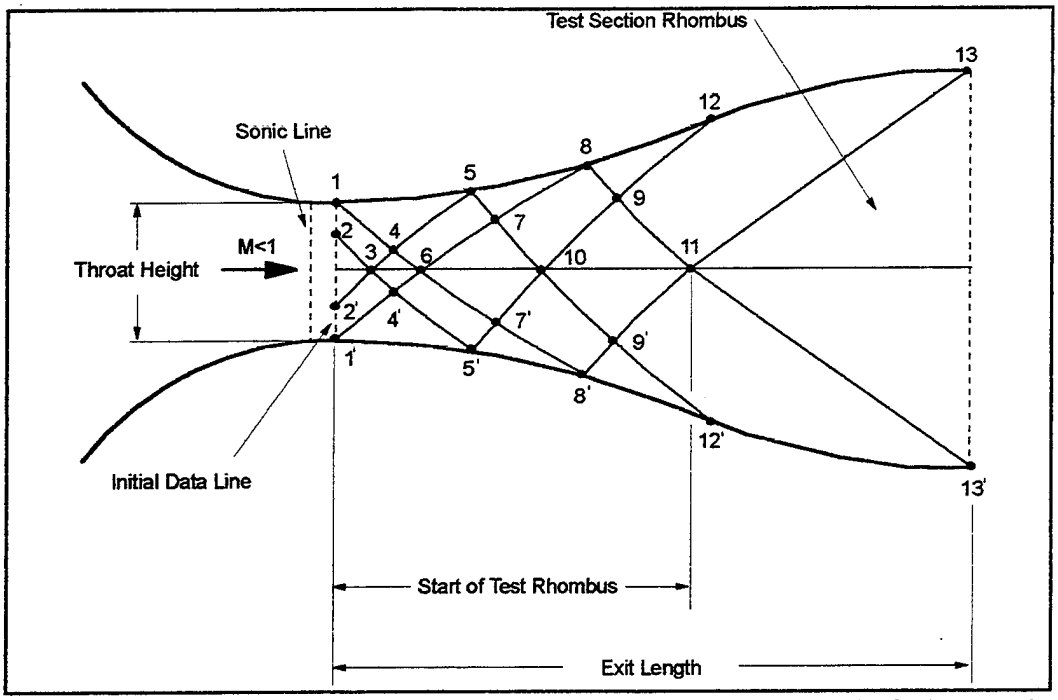


Figure E2. Schematic of Supersonic Nozzle Design by the Method of Characteristics

$$\left(\frac{dy}{dx}\right)_{char} = \tan(\theta \pm \mu)$$

where θ is the angle between the streamline of the flow and the horizontal and μ is the angle between the streamline and the characteristic line; Step 2 -- the determination of the compatibility equations

$$\theta + \nu(M) = \text{const} = K_- \quad \text{(along the right characteristic)}$$
$$\theta - \nu(M) = \text{const} = K_+ \quad \text{(along the left characteristic)}$$

where again θ is the angle between the horizontal and the streamline, and, $\nu(M)$ is the Prandtl-Meyer function, the compatibility equations holding along the characteristics; Step 3 -- the solution of the compatibility equations point by point along the characteristics.

Note: The initial data line used in starting the computation of the method of characteristics in this program begins with the assumption that the sonic line at the throat is straight. A point ΔM downstream of the sonic line along the centerline Mach number distribution is chosen as the initial point for the characteristics procedure. With the combination of this initial point , the centerline distribution, and the radius of curvature at the throat, the method of characteristics is carried out in a marching fashion.

Choosing the option step-by-step will instruct the program to include in the final output all "steps" used in calculating the characteristic net, including local data pertaining to the nodal points comprising the turning angle, the x and y coordinates of the grid points and the Mach number. If in turn the option "wall points only" is exercised, the data associated with the grid points that decide the contour or wall geometry are included in the final output.

Once the last selection for the first category of inputs is chosen and the "enter" key is subsequently struck, the selections made are then displayed in the following format:

NOZZLE = SHORT (REGULAR, EXPONENTIAL)

HEIGHT TO BE READ = EXIT (THROAT)

LENGTH TO BE READ = LENGTH TO EXIT (LENGTH TO RHOMBUS)

OUTPUT FORMAT = STEP-BY-STEP (WALL POINTS)

The question, "Are input values correct?, 1-Yes, 2-No", follows immediately, allowing the opportunity to make changes to the inputs if necessary. Selecting "Yes" causes the following menu to be displayed:

INPUT VALUES TO BE CHANGED (1, 2, 3, 4):

1- TYPE OF NOZZLE: A. SHORT, B. REGULAR, C. EXPONENTIAL

2 - HEIGHT TO BE READ: A. EXIT, B. THROAT

3 - LENGTH TO BE READ: A. EXIT, B. TEST RHOMBUS

4 - TYPE OF OUTPUT: A. STEP-BY-STEP, B. WALL POINTS ONLY

By selecting a value from one to four a sub-menu of the descriptors to the right of the colon of the input chosen is listed. For example, selecting the value of 2 (Height to be read) from the above menu yields

1 - EXIT, 2 - THROAT

prompting a choice of height designation. After hitting the "enter" key, the program will again display the first-category input selections, showing the latest modifications. An opportunity to make additional alterations is also afforded when the question, "Any other changes?, 1-Yes, 2-No", immediately follows. Selection of "No" initiates the sequence of events for data input associated with the second category.

2. CATEGORY 2: NOZZLE FLOW AND GEOMETRY SPECIFICATIONS

Commencement of the sequence of prompts for the second category of inputs is denoted by the statements

"THE NEXT SET OF INPUTS SPECIFY FLOW CHARACTERISTICS AND SPECIFIC GEOMETRY DIMENSIONS FOR THE NOZZLE"

***** PLEASE UTILIZE DECIMAL POINTS FOR THESE INPUTS *****

It is necessary to use decimal points when specifying numeric data; the program is formatted to read the input data in scientific notation, though numeric values may be entered into the program as real numbers. If a decimal point is not explicitly stated, the exponent field in the scientific notation format will reflect this with zeros, resulting in an ambiguous input. Thus, if the real number "14" is the desired input, it must be entered as "14."; this results in the scientific notation representation "0.14000E+02". If the number is entered as "14", the resulting representation will be "0.14000E+00".

The inputs for the second group are outlined as follows:

1. INPUT RATIO OF SPECIFIC HEATS

Self-explanatory.

2. INPUT TEST SECTION MACH NUMBER

The Mach number of the uniform flow that is required at the exit plane of the nozzle.

3. INPUT EXIT LENGTH (INCHES) OR INPUT BEGINNING OF TEST RHOMBUS (INCHES)

The choice made in the first category of inputs concerning the horizontal length will dictate which prompt will be displayed. Refer to Figure E2.

4. INPUT HALF HEIGHT OF EXIT (INCHES) OR INPUT HALF HEIGHT OF THROAT (INCHES)

Again dependent on the selection made in the first category of inputs with reference to the height to be read.

5. INPUT RADIUS OF CURVATURE AT THROAT (INCHES)

Self-explanatory.

6. INPUT MULTIPLICATIVE FACTOR FOR "X" INCREMENT

Influences the spacing between consecutive contour points. A range between 1.0 (representing 150 points to describe the contour) to 0.5 (representing 400 points) is available.

> Note: Generation of the cubic centerline Mach number distribution, which is associated with the regular nozzle contour, is dependent upon the result of a "feasibility expression" involving the second category values input by the user. If the outcome of the expression does not fall into a pre-determined interval, the program halts execution and displays the message,
>
> *** CUBIC CENTERLINE MACH NO. DISTRIBUTION IS NOT APPROPRIATE FOR INPUT GIVEN ***
>
> At this point, the program must be re-initialized and the process of re-entering the input started over. One of the input values, gamma, test section Mach number, exit length or length to test rhombus, exit or throat height, or the radius of curvature, or a combination thereof

must be changed such that the compatibility requirements set forth by the feasibility expression are satisfied.

When the data for the multiplicative factor has been entered and the "enter" key struck the second category of inputs are displayed in the following fashion:

GAMMA = 0.14000E+01
SMT = 0.17000E+01
XEXXT = 0.11500E+02
YTHEX = 0.19500E+01
RCT = 0.11500E+01
DELMUL = 0.70000E+00
ARE INPUT VALUES CORRECT ?, 1 - YES, 2 - NO

where

GAMMA = Ratio of specific heats
SMT = Test section Mach number
XEXXT = Exit length or length to the beginning of test rhombus depending on the choice in first category of inputs
YTHEX = Half height of exit or half height of throat depending on the choice in the first category of inputs
DELMUL = Multiplicative factor for "x" increment

As in the first category of inputs, the option to make changes to the input data is available. When changes are desired a listing of the input descriptors is displayed:

INPUT VALUE TO BE CHANGED: 1 - GAMMA, 2 - SMT,
3 - XEXXT, 4 - YTHEX, 5 - RCT, 6 - DELMUL

A selection will exhibit a directive prompting the user to input the new value. For example, choosing gamma (1) results in,

INPUT NEW VALUE FOR GAMMA

Fulfilling this and subsequently striking the "enter" key causes the second category of inputs to be re-displayed showing the recent modifications. Additional changes may also be conducted at this point if necessary.

If the second category of inputs have been reviewed with satisfaction, the program will begin calculation of the isentropic contour at this point. Conclusion of the routine is indicated by the remarks,

OUTPUT ISENTROPIC DATA FOR NOZZLE CONTOUR
STORED IN FILENAME "outpt1"

DATA FROM THIS FILE TO BE USED IN THE VISCOUS
PROGRAM "nbl6.f" IS STORED IN FILENAME "outpt2"

The file "outpt1" contains a systematic breakdown of the data calculated by the program which are then available to the user for review. A complete explanation and an example of the format are presented in the following section. The file "outpt2" contains the data that are to be utilized in the program "nbl6" and are in a format that is convenient for file processing.

3. "outpt1" EXAMPLE AND DESCRIPTION

Figure E3 shows the format in an example of the file "outpt1". It has been sub-divided into it's major components and labeled for reference below.

1. Introductory Header - Self-explanatory.
2. Descriptive Comments - Refers to the comments made in the first category of inputs when prompted by the program for a description of the project.
3. User Inputs - Encompasses all the inputs into the program made by the user. The input identifiers associated with the first category of inputs are defined as follows:

INDSR = Nozzle Type
INDYTH = Characteristic Height (Throat or Exit)
INDXTE = Characteristic Length (Exit or Test Rhombus)
INDOUT = Output Mode (Step-by-Step or Wall Points)

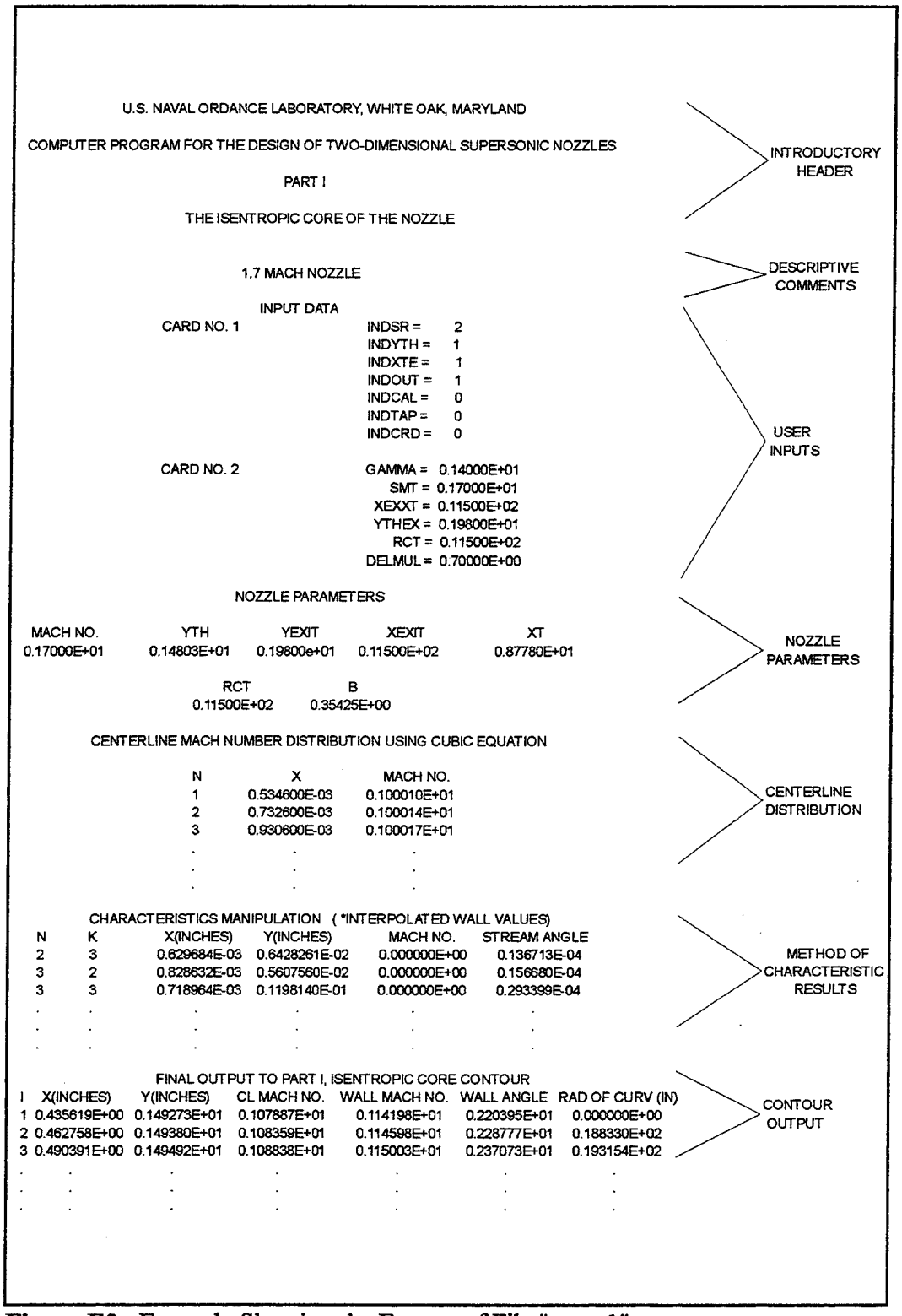


Figure E3. Example Showing the Format of File "outpt1"

INDCAL, INDTAP, and INDCRD are no longer user-accessible. These variables were used in the original software and controlled the medium to be used to record the output data, i.e., magnetic tape or punch cards. The variables have been "hardwired" in order to accommodate the current software modifications for data output management.

The input descriptors for the second category of inputs have been previously defined.

4. Nozzle Parameters - These include, in addition to those dimensions supplied by the user, the "related" values calculated by the program using isentropic relationships or simple geometric relations. Thus, given the input of the throat height the program calculates the exit height ,or, given the horizontal length from the throat to the exit plane the program calculates the length from the throat to the test rhombus. The parameters are defined as,

Mach No. = Nozzle exit Mach number
YTH = Half height of nozzle throat
YEXIT = Half height of nozzle exit
XEXIT = Length between nozzle throat and exit
XT = Length between nozzle throat and test rhombus
RCT = Radius of curvature at throat
* B = Indicates result of "Feasibility Expression"

* Note: The result of the feasibility expression, to determine if the cubic centerline Mach number distribution may be calculated with the given nozzle dimensional inputs, must fall in the interval $-2.0 < B < 1.0$.

5. Centerline Mach Number Distribution - Denotes the centerline location (relative to the throat) and corresponding Mach number. The function used to generate the distribution, i.e., cubic, exponential, etc., is dependent upon the choice of nozzle type (regular, exponential, short).

6. Method of Characteristic Results - Describes the characteristic manipulation used to generate the wall values along the contour.

N = Characteristic line (From left to right)

L = Nodal points along characteristic line

X (inches) = X-coordinate of nodal point

Y (inches) = Y-coordinate of nodal point

Mach No. = Local Mach number at nodal point

Stream angle = Local velocity angle at nodal point with respect to the horizontal

7. Contour Output - Final output of the isentropic core.

X(INCHES) = X - coordinate of isentropic core

Y(INCHES) = Y - coordinate of isentropic core

CL MACH NO. = Centerline Mach number

WALL MACH NO. = Mach number along contoured wall

WALL ANGLE = Wall angle relative to centerline

RAD. OF CURV. (IN) = Radius of curvature

B. MODIFICATION FOR VISCOUS EFFECTS (Program nbl6)

The program "nbl6" modifies the contour of the nozzle to account for the boundary layer formation. Originally, this software considered the boundary layer effects along the contour of the nozzle only and neglected the effects that would be caused with the addition of side walls. To compensate for this deficiency in correcting for boundary layer displacement, the approach used by Demo [Ref. 29: p. 24] was employed. The assumption is made that the displacement thickness is the same on both contoured and side walls. The viscous displacement effects on all surfaces are then summed together and evenly distributed between the two contour surfaces only, as illustrated in Figure E4.

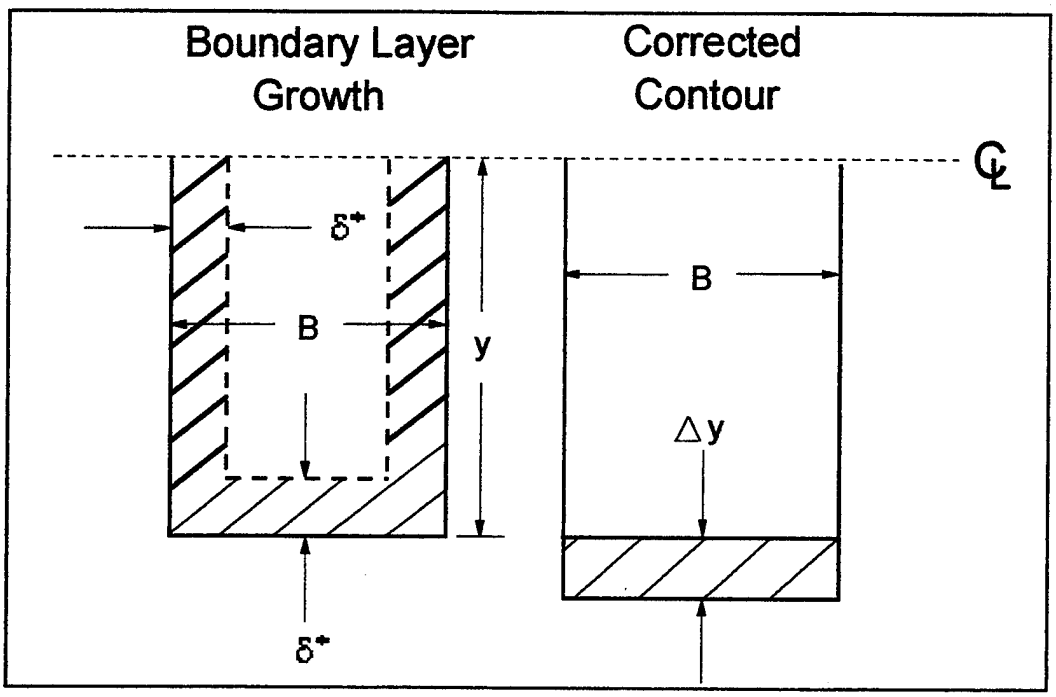


Figure E4. Nozzle Wall Correction for Boundary Layer

Thus, the total displacement area of the entire nozzle cross-section is compensated by modifying only the contoured walls, allowing the side walls to remain flat and parallel. The displacement required to the inviscid contour was calculated using the expression

$$\Delta y = \frac{2y\delta^* + (B - 2\delta^*)\delta^*}{B} \qquad \text{(E1)}$$

where δ^* = displacement thickness, B = nozzle width, and y = half height of the contour. This equation has been incorporated into the software. The final output, discussed later, was modified to reflect this change.

The data-output management structure, as before, is limited to storing data for one run. A successive run will overwrite the data stored from the preceding run.

Input into the program is supplied by both the output from "char6" (i.e., file outpt2) and the user using an interactive presentation similar to that discussed above for the

inviscid contour. The first category of inputs consists of a series of functional mode selections concerned with the thermal and velocity boundary layer behavior. The second category is comprised of numerical input prompts for flow conditions and nozzle dimensions.

1. CATEGORY 1: FUNCTIONAL MODES

The functional modes establish the desired profile behavior that the velocity and thermal boundary layers will undergo while traversing the length of the nozzle. The modes are outlined below.

1. INDICATE WHERE THE BOUNDARY LAYER CALCULATION WILL TAKE PLACE, 1. ALONG CENTERLINE ONLY, 2. ALONG THE WALL ONLY, 3. BOTH THE CENTERLINE AND THE WALL

   Specifying the first option results in the message,

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*          CENTERLINE PARAMETER INPUT DATA                        *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

   indicating that all input into the program from this point will pertain to the effects of the boundary layer along the nozzle centerline. Selection of the second option displays

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*              WALL PARAMETER INPUT DATA                          *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

   indicating further inputs will apply to the effects of the boundary layer along the nozzle contoured walls. Option three effectively causes the program to run twice, once for the effects along the centerline followed by a run associated with the boundary layer effects along the contoured walls. The final output for option three is consolidated as a single output vice individual outputs for each run.

2. INDICATE BOUNDARY LAYER MODE BEGINNING AT NOZZLE THROAT, 1. STRICTLY LAMINAR, 2. STRICTLY TURBULENT, 3. LAMINAR-TRANSITION-TURBULENT

Self-explanatory.

3. INDICATE WALL TEMPERATURE FOR NOZZLE, 1. CONSTANT TEMPERATURE, 2. ADIABATIC WALL, 3. TEMPERATURE DISTRIBUTION ALONG NOZZLE TO BE INPUT BY PROGRAM USER

Wall temperature is assumed only along the contour of the nozzle. Since the boundary layer displacement thickness for the entire cross-section of the nozzle is a function of the displacement thickness generated along the contour, it can be thought of that the temperature distribution exists both on the contour and side walls.

4. INDICATE THE CHARACTERISTIC PARAMETER ON WHICH TRANSITION WILL BE BASED, 1. REYNOLDS NUMBER, 2. "X" DISTANCE FROM THE THROAT

The transition mode only becomes active if the laminar-transition-turbulent selection of the boundary layer mode is chosen. The point of transition from laminar flow to turbulent flow may be based upon a horizontal distance "x" relative to the nozzle throat and along the centerline or a Reynolds number in which the momentum thickness of the boundary layer is used as the characteristic length

The last entry made for the mode options is followed by a listing of the selections to verify the settings:

B.L. MODE = LAMINAR (TURBULENT, LAM-TRANS-TURB)

WALL TEMP. MODE = CONSTANT (ADIABATIC, USER DEFINED)

*TRANSITION PARAMETER = REYNOLDS NUMBER ("X" DISTANCE)

B.L. CALCULATION = CENTERLINE ONLY (WALL ONLY, BOTH CENTERLINE AND WALL)

"ARE INPUT VALUES CORRECT?, 1-YES, 2-NO

*Note: Displayed only if B.L. Mode = Lam-Trans-Turb

If a mode is incorrectly set or a change is desired, "no" is subsequently chosen, resulting in a modification menu:

INPUT VALUE TO BE CHANGED (1,2,3,4):

1. B.L. MODE: A. LAMINAR, B. TURBULENT, C. LAM-TRANS-TURB
2. WALL TEMP. MODE: A. CONSTANT, B. ADIABATIC, C. USER DEFINED
3. B.L. CALCULATION: A. CENTERLINE, B. WALL, C. CENTERLINE AND WALL

*4. TRANSITION: A. REYNOLDS NUMBER, B. "X" TRANSITION

*Note: selection of the transition mode with the B.L. Mode set other than B.L. Mode = Lam-Trans-Turb will result in the message, "Transition parameter not required for inputs given".

The mode to be modified is selected from the menu list, which in turn causes a sub-listing of the options to which the mode may be set to be displayed. For example, if the boundary layer mode is to be changed, its selection from the modification menu would be followed by,

1. LAMINAR, 2. TURBULENT, 3. LAM-TRANS-TURB

A choice of one of the available options sets the mode and then causes a re-display of all the modes and their current status;

B.L. MODE = LAMINAR

WALL TEMP. MODE = CONSTANT

TRANSITION PARAMETER = REYNOLDS NUMBER

B.L. CALCULATION = WALL ONLY

"ANY OTHER CHANGES?, 1-YES, 2-NO"

Other modifications may be done at this point in a sequence similar to that discussed above. If no other changes are required or if the modes initially set were correct, the series of prompts for the second category of inputs will be initiated.

2. CATEGORY 2: FLOW CONDITIONS AND NOZZLE DIMENSIONS

The second category of inputs includes the numerical data associated with the flow conditions, and additional dimensions of the nozzle, which will be made clear below. The onset of the second set of inputs is denoted by the message

* * * PLEASE UTILIZE DECIMAL POINTS FOR THE FOLLOWING INPUTS * * *

followed by the first prompt for information. Decimal points are necessary for the numeric inputs for the reasoning previously explained.

Most of the input prompts are self-explanatory and require no elaboration. Those prompts requiring explanation or having relevant comments will be summarized following the prompt.

1. INPUT REYNOLDS NUMBER FOR TRANSITION
   (Reynolds number based on momentum thickness of boundary layer)

   Displayed only if the boundary layer mode is set to B.L. Mode = Lam-Trans-Turb and the transition indication mode set to Transition Parameter = Reynolds Number.

2. INPUT TRANSITION DISTANCE FROM THE THROAT IN FEET

   Displayed only if the boundary layer mode is set to B.L. Mode = Lam-Trans-Turb and the transition indication mode is set to Transition Parameter = "X" Distance From Throat.

3. INPUT MOMENTUM THICKNESS OF BOUNDARY LAYER AT THE THROAT IN FEET

   A value of 1.0E-5 feet is suggested.

4. INPUT STAGNATION PRESSURE IN LBS/IN^2

5. INPUT TOTAL TEMPERATURE OF SUPPLY MEDIUM IN DEGREES R

6. INPUT TEMPERATURE OF THE WALL IN DEGREES R

   Displayed only if the wall temperature indication mode is set to Wall Temp. Mode = Constant.

7. INPUT THE EXTENSION LENGTH OF NOZZLE PAST THE EXIT IN INCHES AS DEFINED FOR THE ISENTROPIC CORE

   The nozzle contour may be extended past the exit plane of the nozzle, as defined by "char6", if, for instance, a test section is to be added. Assumes uniform duct flow.

8. INPUT INCREMENT OF "X" IN INCHES FOR EXTENSION LENGTH TO INTERPOLATE CONTOUR OF NOZZLE

   Establishes the horizontal distance between consecutive points that describe the contour of the extension length.

9. INPUT WIDTH OF NOZZLE

10. INPUT RATIO OF SPECIFIC HEATS

11. INPUT EXPONENT FOR VISCOSITY-TEMPERATURE RELATION

    For air, this is (ω =) 0.76.

12. INPUT MOLECULAR WEIGHT OF GAS SUPPLY (AIR = 28.97)

13. INPUT SPECIFIC HEAT OF GAS IN BTU/LB-DEG-R (AIR = 0.24)

14. INPUT PRANDTL NUMBER FOR GAS (AIR = 0.72)

Following the conclusion of the last prompt, a listing of all the input descriptors and the values assigned to them is displayed:

*REYNOLDS NUMBER = 0.50000E-02
*"X" TRANSITION = 0.60000E+01
MOMENTUM THICKNESS = 0.10000E-04
STAGNATION PRESSURE = 0.47500E+02
STAGNATION TEMPERATURE = 0.68000E+02
**WALL TEMPERATURE = 0.72000E+02
EXTENSION LENGTH PAST NOZZLE EXIT = 0.12000E+02
INCREMENT "X" FOR EXTENSION = 0.65000E+00
WIDTH OF NOZZLE = 0.40000E+01
GAMMA = 0.14000E+01
VISCOSITY-TEMP. EXPONENT = 0.76000E+00
MOLECULAR WEIGHT OF GAS = 0.28970E+02
SPECIFIC HEAT = 0.24000E+00
PRANDTL NUMBER = 0.72000E+00

"ARE INPUTS CORRECT?, 1-YES, 2-NO"

*Note: Displayed only if boundary layer mode is set to B.L. Mode = 3 and the transition indication mode is set to either Transition Parameter = Reynolds Number or Transition Parameter = "X" Distance from Throat

**Note: Displayed only it the wall temperature indication mode is set to Wall Temp. Mode = Constant

If the option is exercised to change any of the input values, the user will be presented with the following menu:

INPUT VALUE TO BE CHANGED (1,2,3,4,5,6,7,8,9,10,11,12,13):

1. TRANSITION PARAMETER
2. MOMENTUM THICKNESS AT THROAT
3. STAGNATION PRESSURE
4. TOTAL TEMPERATURE
5. WALL TEMPERATURE

6. EXTENSION LENGTH OF NOZZLE
7. "X" INCREMENT FOR EXTENSION LENGTH
8. WIDTH OF NOZZLE
9. RATIO OF SPECIFIC HEATS
10. VISCOSITY-TEMPERATURE EXPONENT
11. MOLECULAR WEIGHT OF GAS
12. SPECIFIC HEAT (Cp) FOR GAS
13. PRANDTL NUMBER

Selection from the menu generates a prompt for the new information to be input for the chosen descriptor. Upon entering the new value and striking the "enter" or "return" key, the list containing the input descriptors and their assigned values will be re-displayed exhibiting the latest changes and soliciting further modifications.

If at this point no other changes are desired and if the wall temperature indication mode is set to an option other than Wall Temp. Mode = Temperature Distribution Input By User, the program will proceed to calculate the modified contour according to the inputs given. If the user has elected to enter a defined temperature distribution along the nozzle contour, the following sequence of prompts can be expected:

INDICATE THE NUMBER OF TEMPERATURE POINTS
TO BE ENTERED. THREE OR MORE POINTS ARE
REQUIRED OR PROGRAM WILL TERMINATE THE DATA
OUTPUT PRIOR TO COMPLETION.

INPUT THE "X" LOCATION FOR POINT NUMBER___
RELATIVE TO THE THROAT

INPUT TEMPERATURE IN DEGREES R FOR POINT
NUMBER ___

The second and third statement are repeated until the number of points designated in the first statement have been entered. When the last point is entered, the program proceeds in

its calculation of the modified contour. Completion of the routine is denoted by the message,

PROGRAM RUN COMPLETE. OUTPUT DATA
TRANSFERRED TO FILE "outpt3"

3. FILE "outpt3" FORMAT DESCRIPTION

Figure E5 illustrates an example of the format used for the output file "outpt3". Again it, as before, has been sub-divided into it's major components and labeled as follows:

1. Functional Modes

*INDINP = 2

*INDPRG = 1

INDMO = 2 (Boundary Layer Mode) where 1 = Laminar, 2 = Turbulent, 3 = Lam-Trans-Turb

INDTW = 1 (Wall Temperature Mode) where 1 = Constant Temp., 2 = Adiabatic, 3 = User Defined Distribution

INDTR =1 (Transition Indication Mode) where 1 = Transition at Reynolds Number, 2 = Transition at "X" Length

*INDCF = 1

*INDOUT = 0

*Note: Indicates values are hardwired into the program and are no longer user accessible

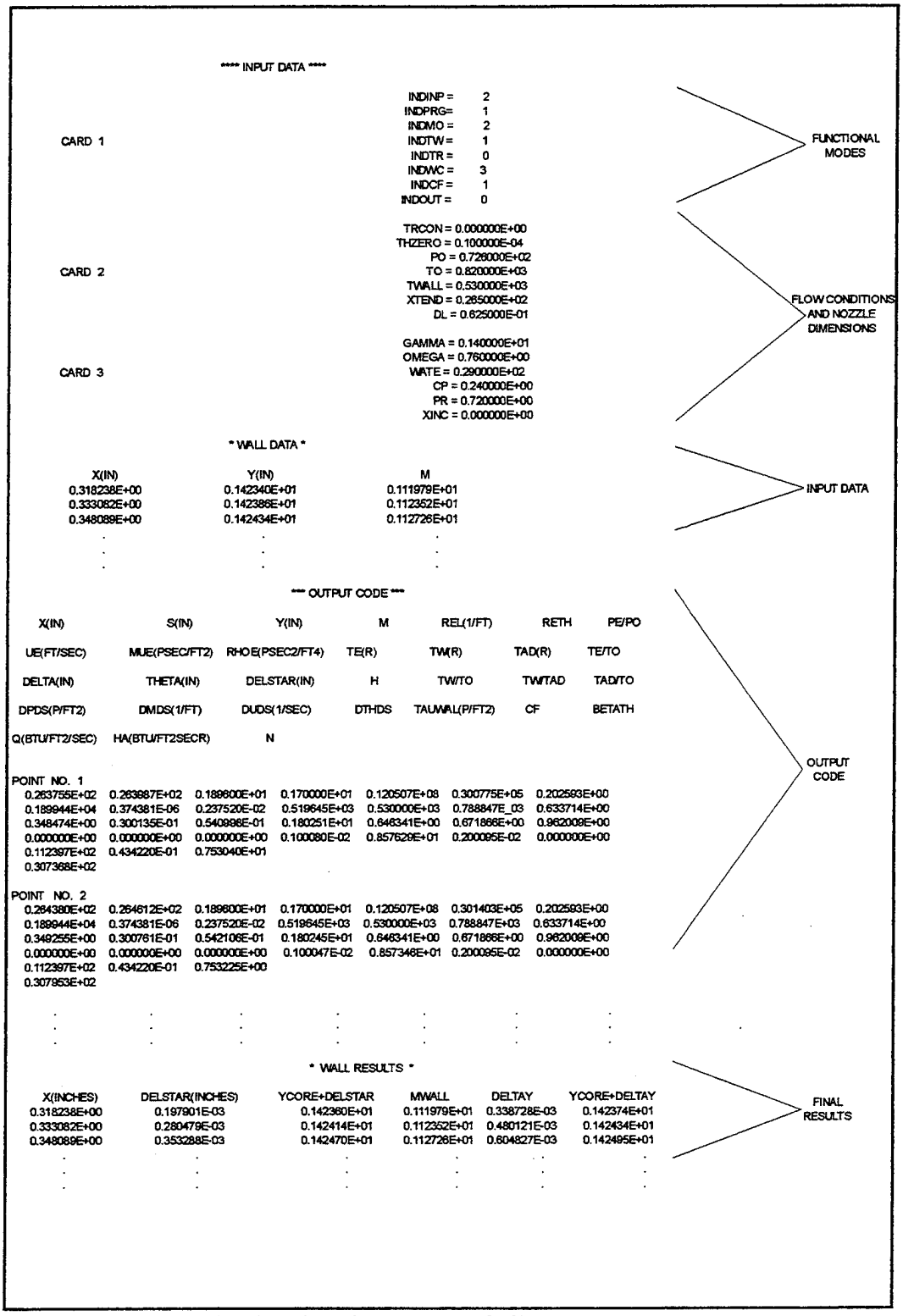


Figure E5. Example Showing the Format of File "outpt3"

2. Flow Conditions and Nozzle Dimensions

TRCON = 0.000000E+00	(Reynolds number value or "x" length depending on the option set in the Transition Indication Mode)
THZERO = 0.100000E-04	(Momentum thickness at nozzle throat)
PO = 0.726000E+02	(Stagnation pressure)
TO = 0.820000E+03	(Stagnation temperature)
TWALL = 0.520000E+03	(Wall temperature when INDTW = 1)
XTEND = 0.265000E+02	(Extension length past nozzle exit plane)
DL = 0.625000E-01	(Increment in "x" of extension length)
GAMMA = 0.140000E+01	(Ratio of specific heats)
OMEGA = 0.76000E+00	(Viscosity-Temperature exponent)
WATE = 0.290000E+02	(Molecular weight of gas)
CP = 0.240000E+00	(Specific heat of gas)
PR = 0.720000E+00	(Prandtl number)
XINC = 0.000000E+00	(Not applicable; hardwired value)

3. Input Data from "outpt2" - Data generated from the inviscid contour software "char6".

4. Output Code - Constitutes the flow properties along the contour of the nozzle calculated by "nbl6" for each set of coordinates that define the nozzle contour.

X (IN)	x - coordinate of contour point
S (IN)	Contour length
Y (IN)	y - coordinate of contour point
M	Mach number along contour
REL (1/FT)	REL = $(\rho U_E)/\mu$
RETH	Reynolds Number; RETH = (REL)(THETA)

PE/PO	Static Pressure / Total Pressure
UE(FT/SEC)	Velocity
MUE (PSEC/FT2)	Absolute Viscosity (μ)
RHOE (PSEC2/FT4)	Density (ρ)
TE (R)	Static Temperature
TW (R)	Wall Temperature
TAD (R)	Adiabatic Wall Temperature
TE/TO	Static Temperature / Total Temperature
DELTA (IN)	Boundary Layer Thickness (δ)
THETA (IN)	Momentum Thickness (θ)
DELSTAR (IN)	Boundary Layer Displacement (δ^*)
H	Form Factor ($H = \delta^*/\theta$)
TW/TO	Wall Temperature / Total Temperature
TW/TAD	Wall Temperature / Adiabatic Wall Temperature
TAD/TO	Adiabatic Wall Temperature / Total Temperature
DPDS (P/FT2)	Change in pressure with respect to surface distance
DMDS (1/FT)	Change in Mach number with respect to surface distance
DUDS (1/SEC)	Change in velocity with respect to surface distance
DTHDS	Change in momentum thickness with respect to surface distance
TAUWAL (P/FT2)	Wall shear stress (τ_w)
CF	Friction Coefficient
Q (BTU/FT2/SEC)	Local rate of heat transfer
HA (BTU/FT2-SEC-R)	Convection heat transfer coefficient

5. Final Results - Modified contour output as calculated by "nbl6"

X (INCHES)	x - coordinate of modified contour
DELSTAR (INCHES)	Boundary layer displacement thickness
YCORE+DELSTAR	Modified contour accounting for boundary layer growth on contoured wall only
MWALL	Mach number at the wall
DELTAY	Modified displacement thickness as determined by the equation modeled by Demo [Ref. 28: p.24].

YCORE+DELTAY	Modified contour accounting for the boundary layer effects contributed by the side walls

C. PROGRAM LISTINGS

Listings are given as follows:

1. Program "char6"
2. Program "nbl6"

```
      PROGRAM CHAR6
*****************************************************************
*  Modified by: LT Douglas L. Seivwright                        *
*  March 1994                                                   *
*                                                               *
*                                                               *
*  INDSR - INDICATE TYPE OF NOZZLE, 1-SHORT, 2-REGULAR, 3-EXPONENTIAL *
*  INDYTH - INDICATE THROAT OR EXIT HEIGHT TO BE READ IN YTHEX  *
*           1-YEXIT, 2-YTH                                      *
*  INDXTE - INDICATE XT OR XEXIT TO BE READ IN XEXXT, 1-XEXIT, 2-XT *
*  INDOUT - INDICATE OUTPUT, 1-STEP BY STEP, 2- WALL POINTS ONLY *
*                                                               *
*  GAMMA - RATIO OF SPECIFIC HEATS (1.4)                        *
*  SMT - TEST SECTION MACH NUMBER                               *
*  XEXXT - EXIT LENGTH OR BEGINNING OF TEST RHOMBUS (INCHES)    *
*  YTHEX - THE HALF HEIGHT OF NOZZLE THROAT OR EXIT DEPENDING ON *
*  INDYTH (INCHES)                                              *
*  RCT - RADIUS OF CURVATURE AT THROAT (INCHES)                 *
*  DELMUL - MULT. FACTOR FOR X INCREMENT (1.0-150 PTS, 0.5-400 PTS) *
*                                                               *
*****************************************************************


      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INTEGER ERROR
      DIMENSION Y(2,400),X(2,400),A(2,400),SM(2,400),ETA(2,400),
     1T(2,400),THE(2,400),XL(600),XW(600),YW(600),SML(600),
     2SMW(600),THEW(600),XCOR(600),FMT(10),R(600),SMLR(400),
     3SMWR(400),XLXEX(400),XLYEX(400),YWYEX(400),XLXT(400)
      CHARACTER*8,FMT
      CHARACTER*20,TYPE1,TYPE2,TYPE3,HGT1,HGT2,LGTH1,LGTH2,
     1OUTPT1,OUTPT2
      CHARACTER*1,TYPNOZ,TYPHGT,TYPLTH,TYPOUT,INSRP
      COMMON Y(2,400),X(2,400),A(2,400),SM(2,400),ETA(2,400),T(2,400)
     1,THE(2,400),XL(600),XW(600),YW(600),SML(600),SMW(600),THEW(600),
     2XCOR(600),FMT(10),   R(600)
      COMMON SMLR(400),SMWR(400),XLXEX(400),XLYEX(400),YWYEX(400)
     1,XLXT(400)

C
C     OUTPT1 IS THE MAIN OUTPUT FILE FOR char6.f WHICH DISPLAYS THE
C     ISENTROPIC CORE DATA OF THE NOZZLE.  OUTPT2 IS THE DATA FROM
C     THE OUTPT1 FILE THAT IS USED FOR THE VISCOUS CALCULATIONS IN
C     nb16.f
C

      OPEN(UNIT=16,FILE='outpt1',STATUS='UNKNOWN')
      OPEN(UNIT=17,FILE='outpt2',STATUS='UNKNOWN')


C
C     DO NOT REMOVE THESE ASSIGNMENT STATEMENTS.  THESE VARIBLES WERE
C     USED IN THE ORIGINAL PROGRAM FORMAT WHICH DETERMINED THE OUTPUT
C     MEDIUM FOR THE DATA, i.e., MAGNETIC TAPE OR PUNCH CARDS.  THE
C     MEANS FOR THIS NO LONGER EXISTS, HOWEVER PORTIONS OF THE PROGRAM
C     STILL REFER TO THESE VARIBLES IN ORDER TO EXECUTE BUT EFFECT THE
C     OUTPUT IN A BENIGN MANNER
C

      INDCAL=0
      INDTAP=0
      INDCRD=0

C
C
C
```



```
      TYPE1 = 'SHORT'
      TYPE2 = 'REGULAR'
      TYPE3 = 'EXPONENTIAL'
      HGT1 = 'EXIT'
      HGT2 = 'THROAT'
      LGTH1 = 'LENGTH TO EXIT'
      LGTH2 = 'LENGTH TO RHOMBUS'
      OUTPT1 = 'STEP-BY-STEP'
      OUTPT2 = 'WALL POINTS'



C
C   INTRODUCTION TO PROGRAM
C

      WRITE(*,30)
   30 FORMAT(1X,/////,1X,15X,'U.S. NAVAL ORDANCE LABORATORY, WHITE'
     1,' OAK, MARYLAND',//,5X,'COMPUTER PROGRAM FOR THE DESIGN OF'
     2' A TWO-DIMENSIONAL SUPERSONIC NOZZLE',//,34X,'PART I',//20X,
     3'THE ISENTROPIC CORE OF THE NOZZLE')
      WRITE(*,23)
   23 FORMAT(1X,/,'Introduction:',//,1X,'This program uses the method'
     1' of characteristics to determine the',/,' contour of a'
     2' two-dimensional isentropic core of a supersonic nozzle.',/,
     3' The program requires two sets of inputs; one that provides the'
     4' general',/,' characteristic lengths and nozzle types that will'
     5' be used to describe',/,' the nozzle; the second set outlines'
     6' the specific flow characteristics',/,' and geometric lengths'
     7' that the contour will be designed to.  The',/,' program is'
     9' currently limited to one output file; in other words,',/,
     1' successive runs will overwrite data generated on previous'
     2' runs.',/)

      PAUSE

C
C   GENERAL CHARACTERISTIC LENGTHS AND NOZZLE TYPE INPUTS
C

      WRITE(*,24)
   24 FORMAT(1X,///////,5X,'THIS SET OF INPUTS PROVIDES THE GENERAL'
     1' CHARACTERISTIC LENGTHS AND',/,10X,' NOZZLE TYPES THAT'
     2' WILL BE USED TO DESCRIBE THE NOZZLE')
      WRITE(*,29)
   29 FORMAT(1X,///,'INPUT A DESCRIPTION OF THE PROJECT')
      READ(*,405)(FMT(I), I=1,10)
  405 FORMAT(10A8)
  901 WRITE(*,31)
   31 FORMAT(1X,//,'INDICATE TYPE OF NOZZLE, 1-SHORT, 2-REGULAR,'
     1' 3-EXPONENTIAL')
      READ(*,32) TYPNOZ
   32 FORMAT(A1)
      IF (TYPNOZ .NE. '1' .AND. TYPNOZ .NE. '2' .AND. TYPNOZ .NE.
     1'3') THEN
        GO TO 901
      END IF
      IF (TYPNOZ .GE. 'A' .AND. TYPNOZ .LE. 'Z') THEN
         GO TO 901
      END IF

  902 WRITE(*,33)
   33 FORMAT(1X,//,'INDICATE THROAT OR EXIT HEIGHT TO BE READ, 1-EXIT,'
     1' 2-THROAT')
      READ(*,34) TYPHGT
   34 FORMAT(A1)
      IF (TYPHGT .NE. '1' .AND. TYPHGT .NE. '2') THEN
         GO TO 902
      END IF
      IF (TYPHGT .GE. 'A' .AND. TYPHGT .LE. 'Z') THEN
         GO TO 902
      END IF
```

```
  903 WRITE(*,35)
   35 FORMAT(1X,//,'INDICATE CHARACTERISTIC HORIZONTAL LENGTH TO BE'
     1' READ, 1-EXIT LENGTH,',/,'2-START OF TEST RHOMBUS')
      READ(*,36) TYPLTH
   36 FORMAT(A1)
      IF (TYPLTH .NE. '1' .AND. TYPLTH .NE. '2') THEN
          GO TO 903
      END IF
      IF (TYPLTH .GE. 'A' .AND. TYPLTH .LE. 'Z') THEN
          GO TO 903
      END IF

  904 WRITE(*,37)
   37 FORMAT(1X,//,'INDICATE OUTPUT, 1-STEP-BY-STEP,'
     1' 2-WALL POINTS ONLY')
      READ(*,38) TYPOUT
   38 FORMAT(A1)
      IF (TYPOUT .NE. '1' .AND. TYPOUT .NE. '2') THEN
          GO TO 904
      END IF
      IF (TYPOUT .GE. 'A' .AND. TYPOUT .LE. 'Z') THEN
          GO TO 904
      END IF


C
C     DISPLAY INPUT RESULTS
C

      IF (TYPNOZ .EQ. '1') THEN
           WRITE(*,1060) 'NOZZLE = ',TYPE1
 1060      FORMAT(1X,//,A9,A5)
      ELSE IF (TYPNOZ .EQ. '2') THEN
           WRITE(*,1061) 'NOZZLE = ',TYPE2
 1061      FORMAT(1X,//,A9,A7)
      ELSE
           WRITE(*,1062) 'NOZZLE = ',TYPE3
 1062      FORMAT(1X,//,A9,A11)
      END IF



      IF (TYPHGT .EQ. '1') THEN
           WRITE(*,1063) 'HEIGHT TO BE READ = ',HGT1
 1063      FORMAT(1X,/,A20,A4)
      ELSE
           WRITE(*,1064) 'HEIGHT TO BE READ = ',HGT2
 1064      FORMAT(1X,/,A20,A6)
      END IF


      IF (TYPLTH .EQ. '1') THEN
           WRITE(*,1065) 'LENGTH TO BE READ = ',LGTH1
 1065      FORMAT(1X,/,A20,A14)
      ELSE
           WRITE(*,1066) 'LENGTH TO BE READ = ',LGTH2
 1066      FORMAT(1X,/,A20,A17)
      END IF


      IF (TYPOUT .EQ. '1') THEN
           WRITE(*,1067) 'OUTPUT FORMAT = ',OUTPT1
 1067      FORMAT(1X,/,A16,A12)
      ELSE
           WRITE(*,1068) 'OUTPUT FORMAT = ',OUTPT2
 1068      FORMAT(1X,/,A16,A11)
      END IF


C
C     CHANGES TO INPUT IF NECESSARY
C
```



```
  905 WRITE(*,39)
   39 FORMAT(1X,//,'ARE INPUT VALUES CORRECT?, 1-YES, 2-NO')
      READ(*,42) INRSP
   42 FORMAT(a1)
      IF (INRSP .NE. '1' .AND. INRSP .NE. '2') THEN
          GO TO 905
      END IF
      IF (INSRP .GE. 'A' .AND. INSRP .LE. 'Z') THEN
          GO TO 905
      END IF
      IF (INRSP .EQ. '2') THEN
 1030     WRITE(*,43)
   43     FORMAT(1X,//,'INPUT VALUE TO BE CHANGED (1,2,3,4):',/,3X,
     1    '1-TYPE OF NOZZLE: A.SHORT, B.REGULAR, C.EXPONENTIAL',/,3X,
     2    '2-HEIGHT TO BE READ: A.EXIT, B.THROAT',/,3X,'3-LENGTH TO BE',
     3    ' READ: A.EXIT, B.TEST RHOMBUS',/,3X,'4-TYPE OF OUTPUT:'
     4    ' A.STEP-BY-STEP, B.WALL POINTS ONLY')
          READ(*,44)INCON
   44     FORMAT(I1)
          IF (INCON .EQ. 1) THEN
 906           WRITE(*,45)
   45           FORMAT(1X,//,'1-SHORT, 2-REGULAR, 3-EXPONENTIAL')
                READ(*,46) TYPNOZ
   46           FORMAT(A1)
          END IF
          IF (TYPNOZ .NE. '1' .AND. TYPNOZ .NE. '2' .AND. TYPNOZ .NE.
     1    '3') THEN
                GO TO 906
          END IF
          IF (TYPNOZ .GE. 'A' .AND. TYPNOZ .LE. 'Z') THEN
                GO TO 906
          END IF
          IF (INCON .EQ. 2) THEN
 907           WRITE(*,47)
   47           FORMAT(1X,//,'1-EXIT, 2-THROAT')
                READ(*,48) TYPHGT
   48           FORMAT(A1)
          END IF
          IF (TYPHGT .NE. '1' .AND. TYPHGT .NE. '2') THEN
                GO TO 907
          END IF
          IF (TYPHGT .GE. 'A' .AND. TYPHGT .LE. 'Z') THEN
                GO TO 907
          END IF
          IF (INCON .EQ. 3) THEN
 908           WRITE(*,49)
   49           FORMAT(1X,//,'1-EXIT, 2-TEST SECTION')
                READ(*,112) TYPLTH
  112           FORMAT(A1)
          END IF
          IF (TYPLTH .NE. '1' .AND. TYPLTH .NE. '2') THEN
                GO TO 908
          END IF
          IF (TYPLTH .GE. 'A' .AND. TYPLTH .LE. 'Z') THEN
                GO TO 908
          END IF
          IF (INCON .EQ. 4) THEN
 909           WRITE(*,113)
  113           FORMAT(1X,//,'1-STEP-BY-STEP, 2-WALL POINTS ONLY')
                READ(*,114) TYPOUT
  114           FORMAT(A1)
          END IF
          IF (TYPOUT .NE. '1' .AND. TYPOUT .NE. '2') THEN
                GO TO 909
          END IF
          IF (TYPOUT .GE. 'A' .AND. TYPOUT .LE. 'Z') THEN
                GO TO 909
          END IF


          IF (TYPNOZ .EQ. '1') THEN
               WRITE(*,1070) 'NOZZLE = ',TYPE1
 1070          FORMAT(1X,//,A9,A5)
```

Program "char6" (cont.)

```
            ELSE IF (TYPNOZ .EQ. '2') THEN
                 WRITE(*,1071) 'NOZZLE = ',TYPE2
 1071            FORMAT(1X,//,A9,A7)
            ELSE
                 WRITE(*,1072) 'NOZZLE = ',TYPE3
 1072            FORMAT(1X,//,A9,A11)
            END IF

            IF (TYPHGT .EQ. '1') THEN
                 WRITE(*,1073) 'HEIGHT TO BE READ = ',HGT1
 1073            FORMAT(1X,/,A20,A4)
            ELSE
                 WRITE(*,1074) 'HEIGHT TO BE READ = ',HGT2
 1074            FORMAT(1X,/,A20,A6)
            END IF

            IF (TYPLTH .EQ. '1') THEN
                 WRITE(*,1075) 'LENGTH TO BE READ = ',LGTH1
 1075            FORMAT(1X,/,A20,A14)
            ELSE
                 WRITE(*,1076) 'LENGTH TO BE READ = ',LGTH2
 1076            FORMAT(1X,/,A20,A17)
                 END IF

            IF (TYPOUT .EQ. '1') THEN
                 WRITE(*,1077) 'OUTPUT FORMAT = ',OUTPT1
 1077            FORMAT(1X,/,A16,A12)
            ELSE
                 WRITE(*,1078) 'OUTPUT FORMAT = ',OUTPT2
 1078            FORMAT(1X,/,A16,A11)
            END IF

 1020       WRITE(*,910)
  910       FORMAT(1X,//,'ANY OTHER CHANGES?, 1-YES, 2-NO')
            READ(*,911) INOUT
  911       FORMAT(I1)
            IF (INOUT .NE. 1 .AND. INOUT .NE. 2) THEN
                 GO TO 1020
            END IF
            IF (INOUT .EQ. 1) THEN
                 GO TO 1030
            END IF
       END IF


C
C     CONVERSION TO INTEGER FORMAT
C

       IF (TYPNOZ .EQ. '1') THEN
            INDSR=1
       ELSE IF (TYPNOZ .EQ. '2') THEN
            INDSR=2
       ELSE
            INDSR=3
       END IF

       IF (TYPHGT .EQ. '1') THEN
            INDYTH=1
       ELSE
            INDYTH=2
       END IF

       IF (TYPLTH .EQ. '1') THEN
            INDXTE=1
       ELSE
            INDXTE=2
       END IF

       IF (TYPOUT .EQ. '1') THEN
            INDOUT=1
       ELSE
            INDOUT=2
```



```
       END IF


C
C     NOZZLE FLOW CHARACTERISTICS AND SPECIFIC GEOMETRY INPUTS
C

       WRITE(*,21)
  21   FORMAT(1X,////,5X,'THE NEXT SET OF INPUTS SPECIFY FLOW'
      1' CHARACTERISTICS AND SPECIFIC',/,18X,' GEOMETRY DIMENSIONS'
      2' FOR THE NOZZLE')
       WRITE(*,22)
  22   FORMAT(1X,//,8X,'***** PLEASE UTILIZE DECIMAL POINTS FOR THESE'
      1' INPUTS *****')

       ERROR=0
 500   WRITE(*,51)
  51   FORMAT(1X,///,'INPUT RATIO OF SPECIFIC HEATS')
       READ(*,52,IOSTAT=ERROR) GAMMA
  52   FORMAT(E10.5)
       IF (ERROR .GT. 0) THEN
            GO TO 500
       END IF


       ERROR=0
 505   WRITE(*,53)
  53   FORMAT(1X,//,'INPUT TEST SECTION MACH NUMBER')
       READ(*,54,IOSTAT=ERROR) SMT
  54   FORMAT(E10.5)
       IF (ERROR .GT. 0) THEN
            GO TO 505
       END IF


       IF (INDXTE .EQ. 1) THEN
            ERROR=0
 510        WRITE(*,55)
  55        FORMAT(1X,//,'INPUT EXIT LENGTH (INCHES)')
            READ(*,56,IOSTAT=ERROR) XEXXT
  56        FORMAT(E10.5)
            IF (ERROR .GT. 0) THEN
                 GO TO 510
            END IF
       ELSE
            ERROR=0
 515        WRITE(*,57)
  57        FORMAT(1X,//,'INPUT BEGINNING OF TEST RHOMBUS (INCHES)')
            READ(*,58,IOSTAT=ERROR) XEXXT
  58        FORMAT(E10.5)
            IF (ERROR .GT. 0) THEN
                 GO TO 515
            END IF
       END IF


       IF (INDYTH .EQ. 1) THEN
            ERROR=0
 520        WRITE(*,59)
  59        FORMAT(1X,//,'INPUT HALF HEIGHT OF EXIT (INCHES)')
            READ(*,61,IOSTAT=ERROR) YTHEX
  61        FORMAT(E10.5)
            IF (ERROR .GT. 0) THEN
                 GO TO 520
            END IF
       ELSE
            ERROR=0
 525        WRITE(*,62)
  62        FORMAT(1X,//,'INPUT HALF HEIGHT OF THROAT (INCHES)')
            READ(*,63,IOSTAT=ERROR) YTHEX
  63        FORMAT(E10.5)
```

Program "char6" (cont.)

```
            IF (ERROR .GT. 0) THEN
                GO TO 525
            END IF
        END IF


        ERROR=0
  530 WRITE(*,64)
   64 FORMAT(1X,//,'INPUT RADIUS OF CURVATURE AT THROAT (INCHES)')
      READ(*,66,IOSTAT=ERROR) RCT
   66 FORMAT(E10.5)
      IF (ERROR .GT. 0) THEN
          GO TO 530
      END IF


      ERROR=0
  535 WRITE(*,67)
   67 FORMAT(1X,//,'INPUT MULTIPLICATIVE FACTOR FOR X INCREMENT'
     1' (1.0-150 PTS, 0.5-400 PTS)')
      READ(*,68,IOSTAT=ERROR) DELMUL
   68 FORMAT(E10.5)
      IF (ERROR .GT. 0) THEN
          GO TO 535
      END IF


C     DISPLAY INPUT RESULTS

      WRITE(*,71) 'GAMMA = ',GAMMA,'SMT = ',SMT,'XEXXT = ',XEXXT,
     1'YTHEX = ',YTHEX,'RCT = ',RCT,'DELMUL = ',DELMUL
   71 FORMAT(1X,//,1X,A9,E10.5,/,5(1X,A9,E10.5,/))


C     CHANGE INPUT VALUES IF NECESSARY

  800 WRITE(*,72)
   72 FORMAT(1X,//,'ARE INPUT VALUES CORRECT?, 1-YES, 2-NO')
      READ(*,73) INANS
   73 FORMAT(I1)
      IF (INANS .NE. 1 .AND. INANS .NE. 2) THEN
          GO TO 800
      END IF

      IF (INANS .EQ. 2) THEN
  801     WRITE(*,74)
   74     FORMAT(1X,//,'INPUT VALUE TO BE CHANGED: 1-GAMMA, 2-SMT,'
     1     ' 3-XEXXT, 4-YTHEX, 5-RCT, 6-DELMUL')
          READ(*,75) INCHG
   75     FORMAT(I1)
          IF (INCHG .EQ. 1) THEN
              ERROR=0
  540         WRITE(*,76)
   76         FORMAT(1X,//,'INPUT NEW VALUE FOR GAMMA')
              READ(*,77,IOSTAT=ERROR) GAMMA
   77         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 540
              END IF
          END IF

          IF (INCHG .EQ. 2) THEN
              ERROR=0
  545         WRITE(*,78)
   78         FORMAT(1X,//,'INPUT NEW VALUE FOR SMT')
              READ(*,79,IOSTAT=ERROR) SMT
   79         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 545
              END IF

          END IF
          IF (INCHG .EQ. 3) THEN
```



```
              ERROR=0
  550         WRITE(*,81)
   81         FORMAT(1X,//,'INPUT NEW VALUE FOR XEXXT')
              READ(*,82,IOSTAT=ERROR) XEXXT
   82         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 550
              END IF
          END IF

          IF (INCHG .EQ. 4) THEN
              ERROR=0
  555         WRITE(*,83)
   83         FORMAT(1X,//,'INPUT NEW VALUE FOR YTHEX')
              READ(*,84,IOSTAT=ERROR) YTHEX
   84         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 555
              END IF
          END IF

          IF (INCHG .EQ. 5) THEN
              ERROR=0
  560         WRITE(*,86)
   86         FORMAT(1X,//,'INPUT NEW VALUE FOR RCT')
              READ(*,87,IOSTAT=ERROR) RCT
   87         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 560
              END IF
          END IF

          IF (INCHG .EQ. 6) THEN
              ERROR=0
  565         WRITE(*,88)
   88         FORMAT(1X,//,'INPUT NEW VALUE FOR DELMUL')
              READ(*,89,IOSTAT=ERROR) DELMUL
   89         FORMAT(E10.5)
              IF (ERROR .GT. 0) THEN
                  GO TO 565
              END IF
          END IF

          WRITE(*,96) 'GAMMA = ',GAMMA,'SMT = ',SMT,'XEXXT = ',XEXXT,
     1    'YTHEX = ',YTHEX,'RCT = ',RCT,'DELMUL = ',DELMUL
   96     FORMAT(1X,//,1X,A9,E10.5,/,5(1X,A9,E10.5,/))

  802     WRITE(*,91)
   91     FORMAT(1X,//,'ANY OTHER CHANGES?, 1-YES, 2-NO')
          READ(*,92) INNEXT
   92     FORMAT(I1)
          IF (INNEXT .NE. 1 .AND. INNEXT .NE. 2) THEN
              GO TO 802
          END IF
          IF (INNEXT .EQ. 1) THEN
              GO TO 801
          END IF
      END IF



      WRITE(16,40)
   40 FORMAT(1X,15X,'U.S. NAVAL ORDANCE LABORATORY, WHITE OAK, MARYLAND'
     1,//,5X,'COMPUTER PROGRAM FOR THE DESIGN OF TWO-DIMENSIONAL'
     2'SUPERSONIC NOZZLES',//,34X,'PART I',//,20X,'THE ISENTROPIC'
     3'CORE OF THE NOZZLE',/////)

      WRITE(16,406)(FMT(I),I=1,10)
  406 FORMAT(20X,10A8////)
      WRITE(16,41)    INDSR,INDYTH,INDXTE,INDOUT,INDCAL,INDTAP,INDCRD,
     1GAMMA,SMT,XEXXT,YTHEX,RCT,DELMUL

   41 FORMAT(          20X,'INPUT DATA',//,20X,'CARD NO. 1',
```


Program "char6" (cont.)

```
     1        5X,'INDSR =',I12,/,34X,'INDYTH =',I12,/,
     734X,'INDXTE =',I12,/,34X,'INDOUT =',I12,/,34X,'INDCAL =',I12/,
     834X,'INDTAP =',I12,/,34X,'INDCRD =',I12//
     520X,'CARD NO. 2', 5X,'GAMMA =',E12.5,/,37X,'SMT =',E12.5,/,35X,
     6'XEXXT =',E12.5,/,35X,'YTHEX =',E12.5,/,37X,'RCT =',E12.5,/,
     934X,'DELMUL =',E12.5)

      EPSC=0.001
      LOLITA=25
      GA=GAMMA+1.
      GB=GAMMA-1.
      GC=2.*GB
      GD=GA/GC
      GE=GA/GB
      GG=2./GB
      GI=GA/2.
      WU=SQRT(GE)
      TERM=(GA/(2.0+GB*SMT**2))**GD
      ETAW=SMT*TERM
      TANA=1./SQRT(SMT**2-1.)
      IF(INDYTH.EQ.1) GO TO 50
      YEXIT=YTHEX/ETAW
      YTH=YTHEX
      GO TO 60
   50 YEXIT=YTHEX
      YTH=YTHEX*ETAW
   60 IF(INDXTE.EQ.1) GO TO 65
      XT=XEXXT
      XEXIT=XT+YEXIT*SQRT(SMT*SMT-1.0)
      GO TO 70
   65 XEXIT=XEXXT
      XT=XEXIT-YEXIT*SQRT(SMT*SMT-1.0)
   70 DO 80 I=1,600
      XW(I)=0.0
      SMW(I)=1.00000
      YW(I)=ETAW
   80 CONTINUE
      GO TO (100,85,98),INDSR
   85 B=XT/2.0/(SMT-1.0)*SQRT(GA/RCT/YTH)-2.0
      IF(B.GT.-2..AND.B.LT.1.0) GO TO 95
      WRITE (16,90) B
   90 FORMAT(1X,///,19X,'** CUBIC CENTERLINE MACH NO. DISTRIBUTION',/,
     123X,'IS NOT APPROPRIATE FOR INPUT GIVEN, B =',E12.6)
      WRITE(*,1200)
 1200 FORMAT(1X,'***CUBIC CENTERLINE MACH NO. DISTRIBUTION IS NOT'
     1' APPROPRIATE FOR INPUT',/,1X,'GIVEN')
      GO TO 98
   95 CALL REG(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA,XEXIT
     1,ETAW,DELMUL)
      GO TO 110
   98 CALL XPO(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA,XEXIT
     1,ETAW,DELMUL)
      GO TO 110
  100 CALL SHO(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA,XEXIT
     1,ETAW,DELMUL)
  110 ASSIGN 740 TO MU
      KAPPA=2
      NEN=NEND-1
      Y(2,1)=0.0
      THE(2,1)=0.0
      T(2,1)=0.0
      ETA(2,1)=0.0
      WRITE(16,111)
  111 FORMAT(1X,///,10X,'CHARACTERISTICS MANIPULATION    '
     1'(* INTERPOLATED WALL VALUES)',//,5X,'N',4X,'K',6X,'X(INCHES)'
     2,5X,'Y(INCHES)',7X,'MACH NO.',5X,'STREAM ANGLE',/)
      DO 900 N=1,NEN
      N1=N
      IF(LASTN.LE.N) GO TO 370
      SM(2,1)=SML(N)
      X(2,1)=XL(N)
      A(2,1)=1./SQRT(SML(N)**2-1.)
      IF(N.GT.1) GO TO 470
```



```
      KO=1
      GO TO 850
  370 X(2,KAPPA)=XL(N)
      Y(2,KAPPA)=(XL(N)-XT)*TANA
      SM(2,KAPPA)=SMT
      A(2,KAPPA)=TANA
      T(2,KAPPA)=0.0
      THE(2,KAPPA)=0.0
      ETA(2,KAPPA)=ETAW*Y(2,KAPPA)
  470 IF(LASTN.GT.N) GO TO 490
      KAPPA=KAPPA+1
  490 DO 700 K=KAPPA,N
      KO=K
      THEL=THE(1,K-1)-WU*ATAN(1./(WU*A(1,K-1)))+ATAN(1./A(1,K-1))
      THER=THE(2,K-1)+WU*ATAN(1./(WU*A(2,K-1)))-ATAN(1./A(2,K-1))
      THE(2,K)=(THEL+THER)/2.
      T(2,K)=SIN(THE(2,K))/COS(THE(2,K))
      CALL ACOM(A(1,K-1),A(2,K-1),WU,THEL,THER,EPSC,LOLITA,A(2,K))
      TAB=(T(2,K-1)+T(2,K))/2.
      AAB=(A(2,K-1)+A(2,K))/2.
      TAA=(T(1,K-1)+T(2,K))/2.
      AAA=(A(1,K-1)+A(2,K))/2.
      SM(2,K)=SQRT(A(2,K)**2+1.)/A(2,K)
      SMAB=(SM(2,K-1)+SM(2,K))/2.
      CAT=(TAB-AAB)/(1.+TAB*AAB)
      DAT=(TAA+AAA)/(1.-TAA*AAA)
      X(2,K)=(Y(1,K-1)-Y(2,K-1)+CAT*X(2,K-1)-DAT*X(1,K-1))/(CAT-DAT)
      Y(2,K)=Y(2,K-1)+CAT*(X(2,K)-X(2,K-1))
      CALL ATE(GA,GD,SMAB,GB,THE(2,K),ETA(2,K-1),X(2,K),X(2,K-1),Y(2,K),
     1Y(2,K-1),SM(2,K-1),SM(2,K),ETA(2,K))
      KIP=K-KAPPA+2
      IF (INDOUT.EQ.2) GO TO 650
      XX=X(2,K)*YEXIT
      YY=Y(2,K)*YEXIT
      THD=THE(2,K)*57.3
      WRITE (16,491) N,K,XX,YY,SM(2,5),THD
  491 FORMAT(1X,2I5,4E15.6)
  650 IF(ETA(2,K).GT.ETAW) GO TO 720
  700 CONTINUE
      GO TO 850
  720 CALL WINTER (ETAW,X(2,K),X(2,K-1),X(2,K-2),ETA(2,K),ETA(2,K-1),ETA
     1(2,K-2),XW(N),K)
      GO TO MU,(740,760)
  740 ASSIGN 760 TO MU
      NO=N1
  760 CALL WINTER(ETAW,Y(2,K),Y(2,K-1),Y(2,K-2),ETA(2,K),ETA(2,K-1),ETA(
     12,K-2),YW(N),K)
      CALL WINTER(ETAW,SM(2,K),SM(2,K-1),SM(2,K-2),ETA(2,K),ETA(2,K-1),E
     1TA(2,K-2),SMW(N),K)
      CALL WINTER (ETAW,THE(2,K),THE(2,K-1),THE(2,K-2),ETA(2,K),ETA(2,K-
     11),ETA(2,K-2),THEW(N),K)
      XX=XW(N)*YEXIT
      YY=YW(N)*YEXIT
      THD=THEW(N)*57.3
      WRITE (16,492) N,K,XX,YY,SMW(N),THD
  492 FORMAT(1X,1H*,2I5,4E15.6)
  850 DO 900 IOTA=1,KO
      X(1,IOTA)=X(2,IOTA)
      Y(1,IOTA)=Y(2,IOTA)
      A(1,IOTA)=A(2,IOTA)
      T(1,IOTA)=T(2,IOTA)
      SM(1,IOTA)=SM(2,IOTA)
      THE(1,IOTA)=THE(2,IOTA)
      ETA(1,IOTA)=ETA(2,IOTA)
  900 CONTINUE
      XW(NEND)=XL(NEND)
      YW(NEND)=1.
      SMW(NEND)=SMT
      THEW(NEND)=0.0
      CALL SETXEQ(XW,NO,XL,SML,NEND)
  960 JO=NEND-NO
      DO 990 J=1,JO
      NJ=NO+J
```


Program "char6" (cont.)

```
      SML(J   )=SML(NJ)
      SMW(J   )=SMW(NJ)
      XL(J   )=XL(NJ)*YEXIT
      XW(J   )=XW(NJ)*YEXIT
      YW(J   )=YW(NJ)*YEXIT
      THEW(J   )=THEW(NJ)*57.3
  990 CONTINUE
      XEXIT=XEXIT*YEXIT
      XT=XT*YEXIT
      J11=JO-1
      DO 991 J4=2,J11
      DS=SQRT((XW(J4+1)-XW(J4-1))**2+(YW(J4+1)-YW(J4-1))**2)
      DTHE=THEW(J4+1)-THEW(J4-1)
      IF(DTHE.EQ.0.0) DTHE=1.E-6
      R(J4)=DS/DTHE*57.3
  991 CONTINUE
      R(1)=0.0
      R(JO)=0.0
      WRITE(16,493)
  493 FORMAT(1X,///,30X,'FINAL OUTPUT TO PART I, ISENTROPIC CORE CONTOUR
     1',//,5X,'I',4X,'X(INCHES)',6X,'Y(INCHES)',5X,'CL MACH NO.',4X,
     2'WALL MACH NO.',3X,'WALL ANGLE',2X,'RAD OF CURV (IN)    ',/)
      WRITE(16,494)(I,XL(I),YW(I),SML(I),SMW(I),THEW(I),R(I),I=1,JO)
  494 FORMAT(1X,I5,6E15.6)
      CONT=0.0

      WRITE(17,142) (FMT(J),J=1,10)
  142 FORMAT(10A8)
      WRITE(17,140)JO,YTH,YEXIT,XT,XEXIT
  140 FORMAT(I5,4E20.7)
      WRITE(17,141)(XL(J),YW(J) ,SMW(J),CONT,SML(J),J=1,JO)
  141 FORMAT(5E20.7)
      END FILE 17
      REWIND 17


      CLOSE(16)
      CLOSE(17)
      WRITE(*,1100)
 1100 FORMAT(1X,///,'OUTPUT ISENTROPIC DATA FOR NOZZLE CONTOUR'
     1,' STORED IN FILENAME outpt1'
     2,///,'DATA FROM THIS FILE TO BE USED IN THE VISCOUS'
     3,' PROGRAM nbl6.f IS STORED',/,'IN FILENAME outpt2')
      STOP
      END



      SUBROUTINE REG(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA
     1,XEXIT,ETAW,DELMUL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION XL(600),SML(600),XCOR(600)
      SKIFG(X)=SMT-(SMT-1.0)*(1.0-B*X/XT)*(1.0-X/XT)*(1.0-X/XT)
      WRITE(16,10) SMT,YTH,YEXIT,XEXIT,XT
   10 FORMAT(1X,////,19X,'NOZZLE PARAMETERS (LENGTHS IN INCHES)'
     1,//,5X,'MACH NO.',5X,'YTH',10X,'YEXIT',7X,'XEXIT',8X,'XT'
     2,/,1X,5E13.5,/)
      WRITE(16,20) RCT,B
   20 FORMAT(1X,27X,'RCT',10X,'B',/,22X,2E13.5,///,10X,
     1'CENTERLINE MACH NUMBER DISTRIBUTION USING CUBIC EQUATION',
     2//,20X,'N',7X,'X',15X,'MACH NO.',/)
      XT=XT/YEXIT
      XEXIT=XEXIT/YEXIT
      XB=0.0
      DO 50 I5=1,600
      XB=XB+0.00001
      SMB=SKIFG(XB)
      IF(SMB.GE.1.0001) GO TO 60
   50 CONTINUE
   60 XL(1)=XB
      SML(1)=SMB
      XCOR(1)=XB*YEXIT
      DELX=0.0001
```



```
      DO 88 I=2,600
      IT=I
      IF(I.LE.20) GO TO 80
      DELX=LOG(100.*(XL(I-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
   80 XL(I)=XL(I-1)+DELX
      XCOR(I)=XL(I)*YEXIT
      SML(I)=SKIFG(XL(I))
      IF(XL(I).GE.XT) GO TO 85
   88 CONTINUE
   85 LASTN=IT
      SML(I)=SMT
      XL(I)=XT
      XCOR(I)=XL(I)*YEXIT
      N1=LASTN+1
      DO 90 J=N1,600
      JTM=J
      DELX=LOG(100.*(XL(J-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
      XL(J)=XL(J-1)+DELX
      XCOR(J)=XL(J)*YEXIT
      SML(J)=SMT
      IF(XL(J). GE. XEXIT) GO TO 95
   90 CONTINUE
   95 NEND=JTM
      XL(NEND)=XEXIT
      XCOR(NEND)=XL(NEND)*YEXIT
      SML(NEND)=SMT
      WRITE(16,100)(K,XCOR(K),SML(K),K=1,NEND)
  100 FORMAT(16X,I5,E15.6,2X,E15.6)
      RETURN
       END
      SUBROUTINE SHO(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA
     1,XEXIT,ETAW,DELMUL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION XL(600),SML(600),XCOR(600)
      SKIFG(X)=((((C6*X+C5)*X+C4)*X+C3)*X+C2)*X+C1
      C1=1.0
      C2=0.023652
      C3=0.80082
      C4=-0.44309
      C5=0.09893
      C6=-0.78644E-2
      ASSIGN 81 TO NU
      XB=0.0
      DO 50 I5=1,600
      XB=XB+0.00001
      XC=XB/ETAW
      SMB=SKIFG(XC)
      IF(SMB.GE.1.0001) GO TO 60
   50 CONTINUE
   60 XL(1)=XB
      SML(1)=SMB
      XCOR(1)=XB*YEXIT
      XEXIT=3.0
      DELX=0.0001
      DO 88 I=2,600
      IT=I
      IF(I.LE.20) GO TO 80
      DELX=LOG(100.*(XL(I-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
   80 XL(I)=XL(I-1)+DELX
      GO TO NU,(81,83)
   81 XCC=XL(I)/ETAW
      IF(XCC.LE.1.60174) GO TO 82
      C1=1.4554
      C2=0.74251
      C3=0.17251
      C4=-0.037244
      C5=0.62572E-2
      C6=-0.34138E-3
      ASSIGN 83 TO NU
      GO TO 83
```


Program "char6" (cont.)

```
   82 XCOR(I)=XL(I)*YEXIT
      XC=XL(I)/ETAW
      SML(I)=SKIFG(XC)
      GO TO 86
   83 XCOR(I)=XL(I)*YEXIT
      XC=LOG(XL(I)/ETAW)
      SML(I)=SKIFG(XC)
   86 IF(SML(I).GE.SMT) GO TO 85
   88 CONTINUE
   85 LASTN=IT
      SML(I)=SMT
      XT=XL(I)
      XCOR(I)=XT*YEXIT
      XEXIT=XT+SQRT(SMT**2-1.)
      N1=LASTN+1
      DO 90 J=N1,600
      JTM=J
      DELX=LOG(100.*(XL(J-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
      XL(J)=XL(J-1)+DELX
      XCOR(J)=XL(J)*YEXIT
      SML(J)=SMT
      IF(XL(J). GE. XEXIT) GO TO 95
   90 CONTINUE
   95 NEND=JTM
      XL(NEND)=XEXIT
      XCOR(NEND)=XL(NEND)*YEXIT
      SML(NEND)=SMT
      WRITE(16,98) SMT,YTH,YEXIT,XCOR(NEND),XCOR(LASTN)
   98 FORMAT(1X,////,19X,'NOZZLE PARAMETERS (LENGTHS IN INCHES)'
     1,//,5X,'MACH NO.',5X,'YTH',10X,'YEXIT',7X,'XEXIT',8X,
     2'XT',/,1X,5E13.5,
     3///,10X,'CENTERLINE MACH NUMBER DISTRIBUTION FOR A SHORT NOZZLE',
     4//,20X,'N',7X,'X',10X,'MACH NO.',/)
      WRITE(16,100)(K,XCOR(K),SML(K),K=1,NEND)
  100 FORMAT(16X,I5,2E15.6)
      RETURN
       END
      SUBROUTINE XPO(XL,SML,XCOR,SMT,YTH,YEXIT,XT,RCT,B,LASTN,NEND,GAMMA
     1,XEXIT,ETAW,DELMUL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION XL(600),SML(600),XCOR(600)
      SKIFG(X)=TM2*(1.-(EXP(C2*(1.-X/XT)*(1.-X/XT))-1.)/TM1)+1.
      DMDX=0.5*SQRT((GAMMA+1.)/RCT/YTH)
      T=DMDX*XT/(SMT-1.)
      ITER=0
      G1=0.001
      T1=2.0
      E1=1.-2./T
      G2=T/2.0
   30 EP=EXP(G2)
      T2=2.*G2*EP/(EP-1.)
      E2=1.-T2/T
      IF(ABS(E2).LE.0.0001) GO TO 45
      B1 =(G2-G1)/(E2-E1)
      ITER=ITER+1
      IF(ITER.GT.50) GO TO 35
      G1=G2
      E1=E2
      G2=G1-B1*E1
      IF(G2.EQ.0.00) G2=0.0001
      GO TO 30
   35 WRITE(16,40) ITER
   40 FORMAT(1X,20X,'ITERATION IN SUB XPO EQUALS',I5)
      STOP
   45 C2=G2
      WRITE(16,47) SMT,YTH,YEXIT,XEXIT,XT
   47 FORMAT(1X,////,19X,'NOZZLE PARAMETERS (LENGTHS IN INCHES)'
     1,//,9X,'MACH NO.',7X,'YTH',10X,'YEXIT',7X,'XEXIT',8X,'XT'
     2,/,5X,5E13.5,/)
      WRITE(16,48) RCT,DMDX,C2
   48 FORMAT(1X,23X,'RCT',8X,'DMT',8X,'C2',/,18X,3E13.5,///,7X,
     1'CENTERLINE MACH NUMBER DISTRIBUTION USING EXPONENTIAL'
```



```
     2'EQUATION',//,23X,'N',7X,'X',10X,'MACH NO.',/)

      TM1=EXP(C2)-1.0
      TM2=SMT-1.0
      XT=XT/YEXIT
      XEXIT=XEXIT/YEXIT
      XB=0.0
      DO 50 I5=1,600
      XB=XB+0.00001
      SMB=SKIFG(XB)
      IF(SMB.GE.1.0001) GO TO 60
   50 CONTINUE
   60 XL(1)=XB
      SML(1)=SMB
      XCOR(1)=XB*YEXIT
      DELX=0.0001
      DO 88 I=2,600
      IT=I
      IF(I.LE.20) GO TO 80
      DELX=LOG(100.*(XL(I-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
   80 XL(I)=XL(I-1)+DELX
      XCOR(I)=XL(I)*YEXIT
      SML(I)=SKIFG(XL(I))
      IF(XL(I).GE.XT) GO TO 85
   88 CONTINUE
   85 LASTN=IT
      SML(I)=SMT
      XL(I)=XT
      XCOR(I)=XL(I)*YEXIT
      N1=LASTN+1
      DO 90 J=N1,600
      JTM=J
      DELX=LOG(100.*(XL(J-1)/XEXIT)+1.)/460.*XEXIT
      DELX=DELX*DELMUL
      XL(J)=XL(J-1)+DELX
      XCOR(J)=XL(J)*YEXIT
      SML(J)=SMT
      IF(XL(J). GE. XEXIT) GO TO 95
   90 CONTINUE
   95 NEND=JTM
      XL(NEND)=XEXIT
      XCOR(NEND)=XL(NEND)*YEXIT
      SML(NEND)=SMT
      WRITE(16,100)(K,XCOR(K),SML(K),K=1,NEND)
  100 FORMAT(18X,I5,2E15.6)
      RETURN
       END
      SUBROUTINE ACOM(P,Q,W,S,R,EPSC,LOLITA,AC)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
 1005 DIMENSION ANOT(100),AP(100)
 1030 ANOT(1)=(P+Q)/2.
 1040 AP(1)=W*ATAN(1./(W*ANOT(1)))-ATAN(1./ANOT(1))+(S-R)/2.

 1050 ANOT(2)=ANOT(1)+.1
 1060 AP(2)=W*ATAN(1./(W*ANOT(2)))-ATAN(1./ANOT(2))+(S-R)/2.

 1070 DO 1110 KOUNT=3,LOLITA
 1080 ANOT(KOUNT)=ANOT(KOUNT-1)-AP(KOUNT-1)*(ANOT(KOUNT-1)-ANOT(KOUNT-2)
     1)/(AP(KOUNT-1)-AP(KOUNT-2))
 1090 AP(KOUNT)=W*ATAN(1./(W*ANOT(KOUNT)))-ATAN(1./ANOT(KOUNT))+(S-R)/2.

 1095 JULES=KOUNT
 1100 IF(ABS((ANOT(KOUNT)-ANOT(KOUNT-1))/ANOT(KOUNT))-EPSC)1145,1145,111
     10
 1110 CONTINUE
 1145 AC=ANOT(JULES)
      IF(JULES.LT.LOLITA) GO TO 1150
      WRITE (16,1146)
 1146 FORMAT(20X,'KOUNT')
 1150 RETURN
       END
      SUBROUTINE WINTER (EXM,R,S,T,XI,XJ,XK,TERP,K)
```

Program "char6" (cont.)

```
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIFF(XI,XJ)=XI-XJ
      DIVAYF(R,S,XI,XJ)=DIFF(R,S)/DIFF(XI,XJ)
      DIVBYF(R,S,T,XI,XJ,XK)=DIVAYF(DIVAYF(R,S,XI,XJ),DIVAYF(S,T,XJ,XK),
     1XI,XK)
      IF (K .EQ. 2) GO TO 10
      TERP=R+DIFF(EXM,XI)*(DIVAYF(R,S,XI,XJ)+DIFF(EXM,XJ)*DIVBYF(R,S,T,X
     1I,XJ,XK))
      GO TO 15
   10 TERP=(EXM-XJ)*R/(XI-XJ)+(EXM-XI)*S/(XJ-XI)
   15 RETURN
       END
      SUBROUTINE ATE(GA,GD,SMAB,GB,THETA,ETA1,X2,X1,Y2,Y1,SM1,SM2,ETA2)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      PQF(FM)=FM*(GA/(2.+GB*FM**2))**GD
      X2X1=X2-X1
      Y2Y1=Y2-Y1
      SNA=.5*(1./SM1+1./SM2)
      ETA2=ETA1+.5*(PQF(SM1)+PQF(SM2))*SNA*SQRT(X2X1*X2X1+Y2Y1*Y2Y1)
      RETURN
       END
      SUBROUTINE SETXEQ(XW,NO,XL,SML,NEND)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION XW(600),XL(600),SML(600),SMM(600)
      DO 70 J=1,600
      JT=J
      IF (XL(J).GE.XW(NO) ) GO TO  71
   70 CONTINUE
   71 K=JT
      KEND=NEND-3
      DO 40 I=NO,NEND
    5 IF(XW(I).LE.XL(K)) GO TO 10
      K=K+1
      GO TO 5
   10 IF(K.LE.KEND) GO TO 20
      GO TO 30
   20 CALL LAGINT(XL(K-2),SML(K-2),5,XW(I),SMM(I),DYO)
      GO TO 40
   30 CALL LAGINT(XL(K-4),SML(K-4),5,XW(I),SMM(I),DYO)
   40 CONTINUE
      DO 60 J=NO,NEND
      XL(J)=XW(J)
      SML(J)=SMM(J)
   60 CONTINUE
      RETURN
       END
      SUBROUTINE LAGINT(X,Y,NPTS,XX,YY,DYY)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(1),Y(1)
      YY=0.
      DYY=0.
      DO 40 I=1,NPTS
      C1=1.
      C2=1.
      DO 10 J=1,NPTS
      IF (J .EQ. I) GO TO 10
      C1=C1*(XX-X(J))
      C2=C2*(X(I)-X(J))
   10 CONTINUE
      SUM=0.
      DO 30 J=1,NPTS
      IF (J .EQ. I) GO TO 30
      C3=1.
      DO 20 K=1,NPTS
      IF (K .EQ. I .OR. K .EQ. J) GO TO 20
      C3=C3*(XX-X(K))
   20 CONTINUE
      SUM=SUM+C3
   30 CONTINUE
      C=Y(I)/C2
      YY=YY+C*C1
      DYY=DYY+C*SUM
   40 CONTINUE
```



```
      RETURN
       END
```

Program "nbl6"


```
      PROGRAM NBL6
*****************************************************************************
*   Modified by: LT Douglas L. Selvwright                                   *
*   March 1994                                                              *
*                                                                           *
*                                                                           *
*   PROGRAM INPUTS:                                                         *
*                                                                           *
*                                                                           *
*                                                                           *
*   INDMO-BOUNDARY LAYER MODE: 1. STRICTLY LAMINAR, 2. STRICTLY             *
*        TURBULENT, 3. LAM-TRANS-TURB                                       *
*   INDTW-WALL TEMP INDICATION: 1. CONSTANT=TWALL, 2. ADIA WALL TEMP,       *
*        3. TEMPERATURE DISTRIBUTION INPUT BY USER                          *
*   INDTR-TRANSITION INDICATION(IF INDMO=3): 1. TRANS AT RETHETA VALUE      *
*        GIVEN IN TRCON, 2. TRANS AT X GIVEN IN TRCON                       *
*   INDWC- INDICATE BOUNDARY LAYER CALCULATION:                             *
*          1. CALCULATE CENTERLINE ONLY, 2. CALCULATE WALL ONLY,            *
*          3. CALCULATE BOTH                                                *
*                                                                           *
*                                                                           *
*   TRCON-TRANSITION CONSTANT EQUAL TO RETHETA (REYNOLDS NUMBER BASED       *
*        ON THE MOMENTUM THICKNESS OF THE BOUNDARY LAYER) OR XTRANS         *
*        (HORIZONTAL DISTANCE RELATIVE TO THE THROAT) DEPENDING             *
*        ON INDTR                                                           *
*   THZERO-THETA (MOMENTUM THICKNESS) AT THROAT IN FEET                     *
*          (USUALLY= 1.0E-5)                                                *
*       PO-STAGNATION PRESSURE IN LBS/IN2                                   *
*       TO-SUPPLY TEMP IN DEGREES R                                         *
*    TWALL-WALL TEMP IN DEGREES R IF INDTW=1                                *
*    XTEND-EXTENSION LENGTH OF NOZZLE WALL PAST EXIT AS DEFINED             *
*          BY THE ISENTROPIC CORE(INCHES) (ASSUMES UNIFORM DUCT FLOW)       *
*       DL-INCREMENT IN X FROM ISENTROPIC EXIT TO EXTENSION LENGTH          *
*          IN (INCHES)                                                      *
*        B-WIDTH OF NOZZLE                                                  *
*                                                                           *
*                                                                           *
*    GAMMA-RATIO OF SPECIFIC HEATS                                          *
*    OMEGA-EXPONENT IN VISCOSITY-TEMP RELATION (AIR=0.76)                   *
*     WATE-MOLECULAR WT OF GAS (AIR=29)                                     *
*       CP-SPECIFIC HEAT OF GAS IN BTU/LB-DEG R  (AIR=0.24)) OR LEAVE       *
*          BLANK AND LET PROGRAM PICK VALUES                                *
*       PR-PRANDTL NUMBER (AIR=0.72)                                        *
*                                                                           *
*                                                                           *
*   ** IFINDTW=3:                                                           *
*      NUM-NUMBER OF WALL TEMP INPUT CARDS (THREE OR MORE POINTS            *
*          ARE REQUIRED OR PROGRAM WILL TERMINATE DATA OUTPUT PRIOR          *
*          TO COMPLETING RUN)                                               *
*       XXX-DISTANCE FROM THROAT IN INCHES                                  *
*       TWW-WALL TEMPS. (DEGREES R) CORRESPONDING TO X=XXX                  *
*                                                                           *
*                                                                           *
*****************************************************************************


       IMPLICIT DOUBLE PRECISION (A-H, O-Z)
       DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
      1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),YSAV(1000),
      2DELTAS(1000),YS(1000),DELY(1000),YYY(1000),YC2DLY(1000)
       CHARACTER*8, FMT
       REAL B
       COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
      1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
      2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
      3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
      4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
      5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
      6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
      7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG,B
       OPEN(UNIT=17,FILE='outpt2',STATUS='UNKNOWN')
       OPEN(UNIT=26,FILE='outpt3',STATUS='UNKNOWN')
       HALF A(1) = .01357623
```



```
       HALF A(2) = .031126762
       HALF A(3) = .047579256
       HALF A(4) = .062314485
       HALF A(5) = .074797995
       HALF A(6) = .084578260
       HALF A(7) = .091301710
       HALF A(8) = .094725305
       HALF A(9) = HALFA(8)
       HALFA(10) = HALFA(7)
       HALFA(11) = HALFA(6)
       HALFA(12) = HALFA(5)
       HALFA(13) = HALFA(4)
       HALFA(14) = HALFA(3)
       HALFA(15) = HALFA(2)
       HALFA(16) = HALFA(1)
       XI(1) = .005299535
       XI(2) = .02771249
       XI(3) = .0671844
       XI(4) = .1222978
       XI(5) = .19106188
       XI(6) = .27099161
       XI(7) = .35919822
       XI(8) = .45249374
       XI(9) = .54750626
       XI(10) = .64080178
       XI(11) = .72900839
       XI(12) = .80893812
       XI(13) = .8777022
       XI(14) = .9328156
       XI(15) = .97228751
       XI(16) = .99470046
       XILN(1) = -5.2401361
       XILN(2) = -3.5858719
       XILN(3) = -2.7003143
       XILN(4) = -2.1012962
       XILN(5) = -1.6551579
       XILN(6) = -1.3056674
       XILN(7) = -1.0238809
       XILN(8) = -0.79298127
       XILN(9) = -0.60238131
       XILN(10) = -.44503503
       XILN(11) = -.31606998
       XILN(12) = -.21203278
       XILN(13) = -.13044784
       XILN(14) = -.069547711
       XILN(15) = -.028103680
       XILN(16) = -.0053135801
C
C  INTRODUCTION TO PROGRAM
C

       WRITE(*,120)
  120  FORMAT(1X,//////,1X,15X,'U.S. NAVAL ORDANCE LABORATORY, WHITE'
      1' OAK, MARYLAND',//,5X,'COMPUTER PROGRAM FOR THE DESIGN OF'
      2' A TWO-DIMENSIONAL SUPERSONIC NOZZLE',//,34X,'PART II',//,15X,
      3'ISENTROPIC CORE CONTOUR MODIFIED FOR VISCOUS EFFECTS')
       WRITE(*,125)
  125  FORMAT(1X,/,'Introduction:',//,1X,'This program modifies the ',
      1'isentropic contour from Part I to take into account',/,'the ',
      2'effects of the boundary layer. The program has been modified to',
      3' take',/,' into account both the boundary layer for the side'
      4' plate as well',/,'as the contour of the nozzle.')

       PRINT*
       PRINT*
       PRINT*
       PRINT*

       PAUSE

       XINC=0.0
       INDCF=1
       INDPRG=2
```

```
      INDINP=2
      ITMES=0
    9 ITMES=ITMES+1
   10 CALL RESTOR
      QSUM=0.0
      DHL=0.0
      CALL IN
      CP1=CP
      CALL DATA
      PRSQR = SQRT (PR)
      PR2MI6 = PR**(-.16666667)
      PRQBRT = PR**(.33333333)
      GO TO (100,110,100),INDMO
  100 L=1
      GO TO 130
  110 L=5
  130 THETA = THZERO
  417 GMUO=(.01298256/(TO+216.))*SQRT ((TO/672.)**3)
      GM1O2=(GAMMA-1.)/2.
      GO1MG=GAMMA/(1.-GAMMA)
      DO 300 N=MIN,MAX
      TETO=1./(1.+((GAMMA-1.)/2.)*(EME(N)**2))
      TE=TETO*TO
      IF (CP1.EQ.0.0) CP=(0.2405-1.186E-05*TE+20.1E-09*TE*TE)
     $  *32.175
  419 AE=SQRT (49764.*GAMMA*TE/WATE)
      UE=EME(N)*AE
      GMUE=2.14E-8*TE**1.5/(TE+180.)
      GMUE=2.27E-08*TE**1.5/(TE+198.6)
  639 POVPO(N)=(1.0+GM1O2*(EME(N)**2))**GO1MG
      RHOE=(POVPO(N)*PO*WATE)/(49764.*TE)
      REL=RHOE*UE/GMUE
      IF(L-4)146,147,148
  146 TADTE = 1. + PRSQR*((TO-TE)/TE)
      GO TO 150
  147 TADTE = 1.+PRSQR*(1.+((PR2MI6-1.)/1600.)*DELTRE)*((TO-TE)/TE)
      GO TO 150
  148 TADTE = 1. + PRQBRT*((TO-TE)/TE)
  150 TAD=TADTE*TE
      GO TO (154,155,160),INDTW
  154 TW(N)=TWALL
      GO TO 160
  155 TW(N)=TAD
  160 TWTE=TW(N)/TE
      DUEDS=(AE*(TO-((GAMMA-1.)/2.)*TE*(EME(N)**2))*DMDS(N))/TO
      DPDS=0.0-RHOE*UE*DUEDS
      IF(L-3) 170,180,180
  170 CALL CHLOE
  175 CALL LAM IT E
      GO TO 190
  180 CALL TRATUR
      IF(L.GE.4) GO TO 190
      L=4
      GO TO 300
  190 DTHDS=CFOV2-THETA*((DMDS(N)*(H+2.-EME(N)**2)*TETO)/EME(N))
      IT=IT+1
      IF(IT.GT.100) THEN
           WRITE(*,191)
  191      FORMAT(1X,'PROGRAM DID NOT COMPLETE RUN; PROGRAM REQUIRES',
     1     'THREE OR MORE TEMPERATURES FOR THE DISTRIBUTION IN ORDER',
     2     'TO COMPLETE RUN')
           STOP
      END IF
      IF (N.LE.MIN) GO TO 200
  225 THETA=THETA2+((OLDDTH+DTHDS)*(S(N)-S(N-1)))/2.
      THTCOR=THBAR-THETA
      IF(ABS (THTCOR/THETA)-.005)200,200,226
  226 THBAR=THETA
  227 IF(L-3)175,180,180
  200 IF(L-3)240,250,250
  240 HA= (CP/(PR**.6))*RHOE*UE*CFOV2*(SQRT (((TE+216.)/(TW(N)+216.))*
     1SQRT (TWTE)))/(1.-A1*(ABS (ENBAR))**B1)
      GO TO 260
```



```
  250 HA=(0.27477951*POVPO(N)*PO*EME(N)/SQRT (TE))*CFOV2
  260 DHEAT=HA*(TAD-TW(N))
      IF(N.EQ.MIN) GO TO 265
  265 TAUWAL=CFOV2*RHOE*(UE**2)
      DELTA=H*THETA
      DELTAS(N)=DELTA
      CALL OUT
      IF(N.EQ.1) GO TO 288
      QSUM=QSUM+(DHEAT+DHL)/2.*(S(N)-S(N-1))
  288 DHL=DHEAT
      WRITE(26,289) QSUM
  289 FORMAT(15X,E15.6)
      IF(INDMO.LE.2)GO TO 1642
  290 CALL IPSO
 1642 OLDDTH=DTHDS
 1643 THBAR=THETA
 1644 THETA2=THETA
      IF(L.EQ.3) GO TO 180
  300 CONTINUE
      N=MAX
      IF(LAP.EQ.1) GO TO 390
      IF(LAP.EQ.2) GO TO 410
  390 WRITE(26,400)
  400 FORMAT(1X,19X,////,55X,'* WALL RESULTS *',//,9X,'N',8X,
     1'X(INCHES)',6X,'DELSTAR(INCHES)',3X,'YCORE+DELSTAR',9X,
     2'MWALL',12X,'DELTAY',9X,'YCORE+DELTAY',//)
  425 DO 426 I7=MIN,MAX
      YSAV(I7)=0.0
  426 CONTINUE
      GO TO 430
  410 WRITE(26,420)
  420 FORMAT(1X,19X,////,60X,'* CENTERLINE RESULTS *',//,9X,'N',8X,
     1'X(INCHES)',6X,'DELSTAR(INCHES)',4X,'0.0+DELSTAR',11X,
     2'M(CL)',11X,'DELTAY',12X,'0.0+DELTAY',//)
  430 DO 450 IA=MIN,MAX
      X(IA)=X(IA)*12.
      YYY(IA)=YY(IA)*12.
      YY(IA)=(YY(IA)+DELTAS(IA))*12.
      DELTAS(IA)=DELTAS(IA)*12.
      DELY(IA)=(2.*YYY(IA)*DELTAS(IA)+(B-2.*DELTAS(IA))*DELTAS(IA))/B
      YYY(IA)=YYY(IA)+DELY(IA)
      YC2DLY(IA)=YSAV(IA)+2*DELY(IA)
      YSAV(IA)=YSAV(IA)+YY(IA)
  450 CONTINUE
      WRITE(26,440)(IA,X(IA),DELTAS(IA),YY(IA),EME(IA),DELY(IA),
     1YYY(IA),IA=MIN,MAX)
  440 FORMAT(5X,I5,6E18.6)
      IF(INDWC.EQ.3.AND.LAP.EQ.1) GO TO 10
      IF(INDWC.NE.3) GO TO 600
  490 WRITE(26,500)
  500 FORMAT(1X,19X,////,45X,'* WALL AND CENTERLINE RESULTS COMBINED *',
     1//,39X,'N',9X,'X(INCHES)',8X,'YCORE+(2)DELSTAR',4X,'YCORE+(2)',
     2'DELTAY',//)
      WRITE(26,510)(I6,X(I6),YSAV(I6),YC2DLY(I6),I6=MIN,MAX)
  510 FORMAT(35X,I5,5X,E15.6,5X,E15.6,5X,E15.6)
  600 IF(XINC.EQ.0.0) GO TO 9
      WRITE(26,630)(FMT(I),I=1,10)
  630 FORMAT(1X,10A8,//,30X,'CONTOUR FOR FLAT PLATE',//,T25,'N',
     1T42,'X',T62,'Y',//)
      S(1)=0.0
      DO 599 I=2,500
      MINC=I-1
      S(I)=S(I-1)+XINC
      IF(S(I).GT.X(MAX)) GO TO 489
  599 CONTINUE
  489 MINX=MIN+1
      DO 620 I=MIN,MAX
      YS(I)=YSAV(I)
      IF(INDWC.NE.3)YS(I)=YY(I)
  620 CONTINUE
      CALL SETXEQ(S,MINX,X,YS,MINC)
      WRITE(26,610)(I,S(I),YS(I),I=2,MINC)
  610 FORMAT(20X,I5,2F20.4)
```

Program "nbl6" (cont.)

```
      WRITE(26,631)(FMT(I),I=1,10)
  631 FORMAT(1X,10A8,//,30X,'CONTOUR FOR TAPERED PLATE',//,T25,'N',
     1T42,'X',T62,'Y',//)
      DO 615 I=2,MINC
      YS(I)=YS(I)+0.021+3.5777E-03*S(I)
  615 CONTINUE
      WRITE(26,610)(I,S(I),YS(I),I=2,MINC)
      GO TO 9
      END

C
C     END MAIN PROGRAM
C


      SUBROUTINE RESTOR
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*8,FMT
      DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
     1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
     2DELY(1000),YYY(1000)
       COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
 1910 CFOV2 =0
 1911 CFOV2L=0.
 1912 CFOV2T=0.
 1913 DELRAT=0.
 1914 DELTA =0.
 1915 DELTRE=0.
 1916 DELTTH=0.
 1917 DHEAT =0.
 1918 DTHDS =0.
 1919 DUEDS =0.
 1920 EN    =0.
 1921 ENBAR =0.
 1922 ENTURB=0.
 1923 H     =0.
 1924 HINC  =0.
 1925 OLDDTH=0.
 1927 QUAY  =0.
 1928 REL   =0.
 1929 RETH  =0.
 1930 RETHTR=0.
 1931 RHOE  =0.
 1932 TAUWAL=0.
 1933 THBAR =0.
 1934 THETA2=0.
 1935 THOVDL=0.
 1936 TLTE  =0.
 1937 ULUE  =1.0E-4
 1938 IT    =0
 1939 L     =0
 1945 N     =0
      MIN=1
   60 DO 61 IA=1,1000
   61 YY(IA)=0.
 1946 RETURN
      END


      SUBROUTINE IN
C     SUBROUTINE IN READS INPUT FROM char6 AND KEYBOARD INPUT
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      INTEGER COUNT,COUNT1,ERROR,INVALD
      CHARACTER*8, FMT
      REAL B
```



```
      CHARACTER*1,INRSP,INCON,INOUT,INANS,INYN,INDIR
      CHARACTER*2,INCHG
      DIMENSION XXX(100),TWW(100),YYS(600),EMES(600),YS(600),EMS(600),
     1X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),
     2S(1000),POVPO(1000),DMDS(1000),FMT(10),DELY(1000),YYY(1000)
      COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG,B

    9 LAP = LAP+1
      IF(LAP.EQ.3 .OR. INDWC .EQ. 1 .OR. INDWC .EQ.2) THEN
           WRITE(*,8)
    8      FORMAT(1X,/////,'PROGRAM RUN COMPLETE. OUTPUT DATA',
     1     ' TRANSFERRED',/,'TO FILE "outpt3".',////)
           STOP
      END IF
      IF (ITMES .EQ. 1) GO TO 14
      GO TO 71
C
C     INPUTS FROM ISENTROPIC CORE DATA GENERATED BY PROGRAM char6
C
   14 ITMES=2
      READ(17,15)(FMT(I),I=1,10)
   15 FORMAT(10A8)
      READ(17,20) MAX,YTH,YEXIT,XT,XEXIT
   20 FORMAT(I5,4E20.7)
      READ(17,25)(X(I),YS(I),EMS(I),YYS(I),EMES(I),I=1,MAX)
   25 FORMAT(5E20.7)

C
C     KEYBOARD INPUTS
C
   71 IF (INDWC .EQ. 3) THEN
           GO TO 28
      END IF

   70 WRITE(*,75)
   75 FORMAT(1X,//,'INDICATE WHERE THE BOUNDARY LAYER CALCULATION WILL'
     1' TAKE PLACE',/,3X,'1. ALONG CENTERLINE ONLY',/,3X,
     2'2. ALONG THE WALL ONLY',/,3X,'3.'
     3' BOTH THE CENTERLINE AND THE WALL')
      READ(*,80) INDWC
   80 FORMAT(A1)

      IF (INDWC .NE. '1' .AND. INDWC .NE. '2' .AND. INDWC .NE. '3') THEN
           GO TO 70
      ELSE IF (INDWC .GE. 'A' .AND. INDWC .LE. 'Z' .OR. INDWC
     1 .GE. 'SP' .AND. INDWC .LE. '/') THEN
           GO TO 70
      END IF


      IF (INDWC .EQ. '2' .OR. INDWC .EQ. '3') THEN
           WRITE(*,26)
   26      FORMAT(1X,///////,17X,'**********************************',
     1     /,17X,'*                                *',/,17X,'*    ',
     2     'WALL PARAMETER INPUT DATA     *',/,17X,'*                ',
     3     '                *',/,17X,'**********************************'
     4     '*******')
      END IF
   28 IF (LAP .EQ. 2 .OR. INDWC .EQ. '1') THEN
           WRITE(*,27)
   27      FORMAT(1X,///////,17X,'**********************************',
     1     '********',/,17X,'*                                *',
     2     ' *',/,17X,'*    CENTERLINE PARAMETER INPUT DATA     *',/,17X,
     3     '*                                *',/,17X,'*******',
     5     '**********************************')
      END IF
```


Program "nbl6" (cont.)

```
   29 WRITE(*,30)
   30 FORMAT(1X,///,'INDICATE BOUNDARY LAYER MODE BEGINNING AT NOZZLE',
     1' THROAT',/,3X,'1. STRICTLY LAMINAR',/,3X,'2. STRICTLY TURBULENT',
     2/,3X,'3. LAMINAR-TRANSITION-TURBULENT')
      READ(*,35) INDMO
   35 FORMAT(A1)

      IF (INDMO .NE. '1' .AND. INDMO .NE. '2' .AND. INDMO .NE. '3') THEN
          GO TO 29
      ELSE IF (INDMO .GE. 'A' .AND. INDMO .LE. 'Z' .OR. INDMO
     1 .GE. 'SP' .AND. INDMO .LE. '/') THEN
          GO TO 29
      END IF


   40 WRITE(*,45)
   45 FORMAT(1X,//,'INDICATE WALL TEMPERATURE FOR NOZZLE',/,3X,
     1'1. CONSTANT TEMPERATURE',/,3X,'2. ADIABATIC WALL',/,3X,
     2'3. TEMPERATURE DISTRIBUTION ALONG NOZZLE TO BE INPUT BY'
     3' PROGRAM USER')
      READ(*,50) INDTW
   50 FORMAT(A1)

      IF (INDTW .NE. '1' .AND. INDTW .NE. '2' .AND. INDTW .NE. '3') THEN
          GO TO 40
      ELSE IF (INDTW .GE. 'A' .AND. INDTW .LE. 'Z' .OR. INDTW
     1 .GE. 'SP' .AND. INDTW .LE. '/') THEN
          GO TO 40
      END IF


      IF (INDMO .EQ. '3') THEN
   55     WRITE(*,60)
   60     FORMAT(1X,//,'INDICATE THE CHARACTERISTIC PARAMETER THAT'
     1    ' TRANSITION WILL BE BASED',/,3X,'1. REYNOLDS NUMBER',
     2    /,3X,'2. "X" DISTANCE FROM THE THROAT')
          READ(*,65) INDTR
   65     FORMAT(A1)

          IF (INDTR .NE. '1' .AND. INDTR .NE. '2') THEN
              GO TO 55
          ELSE IF (INDTR .GE. 'A' .AND. INDTR .LE. 'Z' .OR. INDTR
     1    .GE. 'SP' .AND. INDTR .LE. '/') THEN
              GO TO 55
          END IF
      END IF

      IF (INDWC .EQ. 3) THEN
          GO TO 224
      END IF



C
C     DISPLAY/RE-DISPLAY KEYBOARD INPUT RESULTS
C

  224 COUNT=0
  225 IF (INDMO .EQ. '1') THEN
          WRITE(*,85)
   85     FORMAT(1X,////,'B.L. MODE = LAMINAR')
      ELSE IF (INDMO .EQ. '2') THEN
          WRITE(*,90) THEN
   90     FORMAT(1X,////,'B.L. MODE = TURBULENT')
      ELSE IF (INDMO .EQ. '3') THEN
          WRITE(*,95)
   95     FORMAT(1X,////,'B.L. MODE = LAM.-TRANS.-TURB.')
      END IF

      IF (INDTW .EQ. '1') THEN
          WRITE(*,100)
```



```
  100     FORMAT(1X,/,'WALL TEMP. MODE = CONSTANT')
      ELSE IF (INDTW .EQ. '2') THEN
          WRITE(*,105)
  105     FORMAT(1X,/,'WALL TEMP. MODE = ADIBATIC')
      ELSE IF (INDTW .EQ. '3') THEN
          WRITE(*,110)
  110     FORMAT(1X,/,'WALL TEMP. MODE = USER DEFINED DISTRIBUTION')
      END IF

      IF (INDMO .EQ. '3') THEN
          IF (INDTR .EQ. '1') THEN
              WRITE(*,115)
  115         FORMAT(1X,/,'TRANSITION PARAMETER = REYNOLDS NUMBER')
          ELSE IF (INDTR .EQ. '2') THEN
              WRITE(*,120)
  120         FORMAT(1X,/,'TRANSITION PARAMETER = "X" DISTANCE FROM'
     1        ' THROAT')
          END IF
      END IF

      IF (INDWC .EQ. '1') THEN
          WRITE(*,125)
  125     FORMAT(1X,/,'B.L. CALCULATION = CENTERLINE ONLY')
      ELSE IF (INDWC .EQ. '2') THEN
          WRITE(*,130)
  130     FORMAT(1X,/,'B.L. CALCULATION = WALL ONLY')
      ELSE IF (INDWC .EQ. '3') THEN
          WRITE(*,135)
  135     FORMAT(1X,/,'B.L. CALCULATION = BOTH WALL AND CENTERLINE')
      END IF


C
C     CHANGES TO KEYBOARD INPUTS
C

      IF (COUNT .EQ. 0) THEN
  150     WRITE(*,140)
  140     FORMAT(1X,///,'ARE INPUT VALUES CORRECT?, 1-YES, 2-NO')
          READ(*,145) INRSP
  145     FORMAT(A1)
          INOUT = '1'
          IF (INRSP .NE. '1' .AND. INRSP .NE. '2') THEN
              GO TO 150
          ELSE IF (INRSP .GE. 'A' .AND. INRSP .LE. 'Z' .OR. INRSP
     1    .GE. 'SP' .AND. INRSP .LE. '/') THEN
              GO TO 150
          END IF
      END IF

      IF (COUNT .GT. 0) THEN
  165     WRITE(*,155)
  155     FORMAT(1X,//,'ANY OTHER CHANGES?, 1-YES, 2-NO')
          READ(*,160) INOUT
  160     FORMAT(A1)
          INRSP = '2'
          IF (INOUT .NE. '1' .AND. INOUT .NE. '2') THEN
              GO TO 165
          ELSE IF (INOUT .GE. 'A' .AND. INOUT .LE. 'Z' .OR. INOUT
     1    .GE. 'SP' .AND. INOUT .LE. '/') THEN
              GO TO 165
          END IF
      END IF



      IF (INRSP .EQ. '2' .AND. INOUT .EQ. '1') THEN
  180     WRITE(*,170)
  170     FORMAT(1X,///,'INPUT VALUE TO BE CHANGED (1,2,3,4):',/,3X,
     1    '1. B.L. MODE: A.LAMINAR, B.TURBULENT, C.LAM-TRANS-TURB',
     2    /,3X,'2. WALL TEMP. MODE: A.CONSTANT, B.ADIABATIC, C.USER'
     3    ' DEFINED',/,3X,'3. B.L. CALCULATION: A.CENTERLINE,'
```

Program "nbl6" (cont.)

```
     4      ' B.WALL, C.CENTERLINE AND WALL',/,3X,'4. TRANSITION:'
     5      ' A. REYNOLDS NUMBER, B. "X" TRANSITION')
            READ(*,175) INCON
   175      FORMAT(A1)
            IF (INCON .NE. '1' .AND. INCON .NE. '2' .AND. INCON .NE. '3'
     1      .AND. INCON .NE. '4') THEN
                GO TO 180
            ELSE IF (INCON .GE. 'A' .AND. INCON .LE. 'Z' .OR. INCON
     1      .GE. 'SP' .AND. INCON INCON .LE. '/') THEN
                GO TO 180
            END IF
            IF (INCON .EQ. '1') THEN
                WRITE(*,181)
   181          FORMAT(1X,//,'1.LAMINAR, 2.TURBULENT, 3.LAM-TRANS-TURB')
                READ(*,185) INDMO
   185          FORMAT(A1)
                    IF (INDMO .EQ. '3') THEN
                        WRITE(*,186)
   186                  FORMAT(1X,//,'SELECT TRANSITION PARAMETER',/,
     1                  3X,'1. REYNOLDS NUMBER, 2. "X" TRANS.')
                        READ(*,187) INDTR
   187                  FORMAT(A1)
                    END IF
            ELSE IF (INCON .EQ. '2') THEN
                WRITE(*,190)
   190          FORMAT(1X,//,'1.CONSTANT, 2.ADIABATIC, 3.USER DEFINED')
                READ(*,195) INDTW
   195          FORMAT(A1)
            ELSE IF (INCON .EQ. '3') THEN
                WRITE(*,200)
   200          FORMAT(1X,//,'1.CENTERLINE, 2.WALL, 3. BOTH')
                READ(*,205) INDWC
   205          FORMAT(A1)
            ELSE IF (INCON .EQ. '4') THEN
                IF (INDMO .EQ. '3') THEN
                    WRITE(*,210)
   210              FORMAT(1X,//,'1. REYNOLDS NUMBER, 2. "X" TRANS.')
                    READ(*,215) INDTR
   215              FORMAT(A1)
                ELSE
                    WRITE(*,220)
   220              FORMAT(1X,//,'*******************************'
     1              '****************************************',/,'*  '
     2              '                                         '
     4              '          *',/,'*',11X,'TRANSITION'
     5              ' PARAMETER NOT REQUIRED FOR INPUTS GIVEN',9X,'*',
     6              ,/,'*                                         '
     7              '                  *',/,'***************'
     8              '****************************************'
     9              '**********')
                END IF
            END IF
        COUNT=COUNT+1
        GO TO 225
        END IF


C
CC    SECOND SET OF INPUT KEYBOARD DATA
C

        WRITE(*,230)
  230 FORMAT(1X,/////////,7X,'*****PLEASE UTILIZE DECIMAL POINTS FOR'
     1' THE FOLLOWING INPUTS*****')
        IF (INDMO .EQ. '3') THEN
            ERROR=0
            IF (INDTR .EQ. '1') THEN
   231          WRITE(*,235)
   235          FORMAT(1X,/////,'INPUT REYNOLDS NUMBER FOR TRANSITION',
     1          /,5X,'(*****REYNOLDS NUMBER BASED ON MOMENTUM THICKNESS'
     2          ' OF BOUNDARY LAYER*****)')
                READ(*,240,IOSTAT=ERROR) TRCON
   240          FORMAT(E10.3)
```



```
                IF (ERROR .GT. 0) THEN
                    GO TO 231
                END IF
            ELSE IF (INDTR .EQ. '2') THEN
   241          WRITE(*,245)
   245          FORMAT(1X,//,'INPUT TRANSITION DISTANCE FROM THE'
     1          'THROAT IN FEET')
                READ(*,250,IOSTAT=ERROR) TRCON
   250          FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 241
                END IF
            END IF
        END IF

        ERROR=0
   251 WRITE(*,255)
   255 FORMAT(1X,//,'INPUT MOMENTUM THICKNESS OF BOUNDARY LAYER AT'
     1' THE THROAT IN FEET',/,'(USUALLY = 1.0E-5 FEET)')
        READ(*,260,IOSTAT=ERROR) THZERO
   260 FORMAT(E10.3)
        IF (ERROR .GT. 0) THEN
            GO TO 251
        END IF

        ERROR=0
   261 WRITE(*,265)
   265 FORMAT(1X,//,'INPUT STAGNATION PRESSURE IN LBS/IN2')
        READ(*,270,IOSTAT=ERROR) PO
   270 FORMAT(E10.3)
        IF (ERROR .GT. 0) THEN
            GO TO 261
        END IF

        ERROR=0
   271 WRITE(*,275)
   275 FORMAT(1X,//,'INPUT TOTAL TEMPERATURE OF SUPPLY MEDIUM IN'
     1' DEGREES R')
        READ(*,280,IOSTAT=ERROR) TO
   280 FORMAT(E10.3)
        IF (ERROR .GT. 0) THEN
            GO TO 271
        END IF


   281 IF (INDTW .EQ. '1') THEN
            ERROR=0
            WRITE(*,285)
   285      FORMAT(1X,//,'INPUT TEMPERATURE OF THE WALL IN DEGREES R')
            READ(*,290,IOSTAT=ERROR) TWALL
   290      FORMAT(E10.3)
            IF (ERROR .GT. 0) THEN
                GO TO 281
            END IF
        END IF

        ERROR=0
   291 WRITE(*,295)
   295 FORMAT(1X,//,'INPUT THE EXTENSION LENGTH OF NOZZLE PAST THE EXIT'
     1' IN INCHES AS',/,'DEFINED FOR THE ISENTROPIC CORE')
        READ(*,300,IOSTAT=ERROR) XTEND
   300 FORMAT(E10.3)
        IF (ERROR .GT. 0) THEN
            GO TO 291
        END IF

        ERROR=0
   301 WRITE(*,305)
   305 FORMAT(1X,//,'INPUT INCREMENT OF "X" IN INCHES FOR'
     1' EXTENSION LENGTH TO INTERPOLATE',/,'CONTOUR OF NOZZLE')
        READ(*,310,IOSTAT=ERROR) DL
   310 FORMAT(E10.3)
        IF (ERROR .GT. 0) THEN
```

```
          GO TO 301
      END IF

      ERROR=0
  311 WRITE(*,315)
  315 FORMAT(1X,//,'INPUT WIDTH OF NOZZLE IN INCHES (ASSUMING'
     1' CONSTANT WIDTH)')
      READ(*,320,IOSTAT=ERROR) B
  320 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 311
      END IF

      ERROR=0
  321 WRITE(*,325)
  325 FORMAT(1X,//,'INPUT RATIO OF SPECIFIC HEATS')
      READ(*,330,IOSTAT=ERROR) GAMMA
  330 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 321
      END IF

      ERROR=0
  331 WRITE(*,335)
  335 FORMAT(1X,//,'INPUT EXPONENT FOR VISCOSITY-TEMPERATURE RELATION'
     1' (FOR AIR OMEGA = 0.76)')
      READ(*,340,IOSTAT=ERROR) OMEGA
  340 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 331
      END IF

      ERROR=0
  341 WRITE(*,345)
  345 FORMAT(1X,//,'INPUT MOLECULAR WEIGHT OF GAS SUPPLY (AIR = 28.97)')
      READ(*,350,IOSTAT=ERROR) WATE
  350 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 341
      END IF

      ERROR=0
  351 WRITE(*,355)
  355 FORMAT(1X,//,'INPUT SPECIFIC HEAT OF GAS IN BTU/LB-DEG-R (AIR ='
     1' 0.24)')
      READ(*,356,IOSTAT=ERROR) CP
  356 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 351
      END IF

      ERROR=0
  361 WRITE(*,357)
  357 FORMAT(1X,//,'INPUT PRANDTL NUMBER FOR GAS (AIR = 0.72)')
      READ(*,358,IOSTAT=ERROR) PR
  358 FORMAT(E10.3)
      IF (ERROR .GT. 0) THEN
          GO TO 361
      END IF


C
C     DISPLAY/RE-DISPLAY INPUTS
C

      COUNT1=0
  635 IF (INDMO .EQ. '3') THEN
          IF (INDTR .EQ. '1') THEN
              WRITE(*,365) 'REYNOLDS NUMBER = ',TRCON
  365         FORMAT(1X,3X,A18,E10.3)
          ELSE IF (INDTR .EQ. '2') THEN
              WRITE(*,370) '"X" TRANSITION = ',TRCON
  370         FORMAT(1X,3X,A17,E10.3)
```



```
          END IF
      END IF

      WRITE(*,375) 'MOMENTUM THICKNESS = ',THZERO
  375 FORMAT(1X,/,3X,A21,E10.3)

      WRITE(*,380) 'STAGNATION PRESSURE = ',PO
  380 FORMAT(1X,/,3X,A22,E10.3)

      WRITE(*,385) 'STAGNATION TEMPERATURE = ',TO
  385 FORMAT(1X,/,3X,A25,E10.3)

      IF (INDTW .EQ. '1') THEN
          WRITE(*,390) 'WALL TEMPERATURE = ',TWALL
  390     FORMAT(1X,/,3X,A19,E10.3)
      END IF

      WRITE(*,391) 'EXTENSION LENGTH PAST NOZZLE EXIT= ',XTEND
  391 FORMAT(1X,/,3X,A35,E10.3)

      WRITE(*,395) 'INCREMENT "X" FOR EXTENSION = ',DL
  395 FORMAT(1X,/,3X,A30,E10.3)

      WRITE(*,400) 'WIDTH OF NOZZLE = ',B
  400 FORMAT(1X,/,3X,A18,E10.3)

      WRITE(*,405) 'GAMMA = ',GAMMA
  405 FORMAT(1X,/,3X,A8,E10.3)

      WRITE(*,410) 'VISCOSITY-TEMP. EXPONENT = ',OMEGA
  410 FORMAT(1X,/,3X,A27,E10.3)

      WRITE(*,415) 'MOLECULAR WEIGHT OF GAS = ',WATE
  415 FORMAT(1X,/,3X,A26,E10.3)

      WRITE(*,420) 'SPECIFIC HEAT (CP) = ',CP
  420 FORMAT(1X,/,3X,A21,E10.3)

      WRITE(*,425) 'PRANDTL NUMBER = ',PR
  425 FORMAT(1X,/,3X,A17,E10.3)

      IF (INVALD .EQ. 1) THEN
          WRITE(*,431)
  431     FORMAT(1X,///,'*****INPUT NOT NECESSARY FOR DATA',
     1    ' PREVIOUSLY GIVEN*****')
      END IF


C
C     CHANGES TO INPUT
C

      INVALD=0
      IF (COUNT1 .EQ. 0) THEN
  445     WRITE(*,435)
  435     FORMAT(1X,///,'ARE INPUTS CORRECT?, 1-YES, 2-NO')
          READ(*,440) INANS
  440     FORMAT(A1)
          INDIR = '1'
          IF (INANS .NE. '1' .AND. INANS .NE. '2') THEN
              GO TO 445
          ELSE IF (INANS .GE. 'A' .AND. INANS .LE. '2') THEN
              GO TO 445
          END IF
      END IF

      IF (COUNT1 .GT. 0) THEN
  460     WRITE(*,450)
  450     FORMAT(1X,///,'ANY OTHER CHANGES?, 1-YES, 2-NO')
          READ(*,455) INDIR
  455     FORMAT(A1)
          INANS = '2'
          IF (INDIR .NE. '1' .AND. INDIR .NE. '2') THEN
```


Program "nbl6" (cont.)

```
                GO TO 460
            ELSE IF (INDIR .GE. 'A' .AND. INDIR .LE. 'Z') THEN
                GO TO 460
            END IF
        END IF

        IF (INANS .EQ. '2' .AND. INDIR .EQ. '1') THEN
1150        WRITE(*,465)
 465        FORMAT(1X,//,'INPUT VALUE TO BE CHANGED (1,2,3,4,5,6,7,8,9'
     1      ',10,11,12,13):',/,3X,'1. TRANSITION PARAMETER',/,3X,
     2      '2. MOMENTUM THICKNESS AT THROAT',/,3X,'3. STAGNATION'
     3      ' PRESSURE',/,3X,'4. TOTAL TEMPERATURE',/,3X,'5. WALL'
     4      ' TEMPERATURE',/,3X,'6. EXTENSION LENGTH OF NOZZLE',/,3X,
     5      '7. "X" INCREMENT FOR EXTENSION LENGTH',/,3X,'8. WIDTH'
     6      ' OF NOZZLE',/,3X,'9. RATIO OF SPECIFIC HEATS',/,2X,'10. '
     7      'VISCOSITY TEMPERATURE EXPONENT',/,2X,'11. MOLECULAR WEIGHT'
     8      ' OF GAS',/,2X,'12. SPECIFIC HEAT (CP) FOR GAS',/,2X,'13. '
     9      'PRANDTL NUMBER')
            READ(*,470) INCHG
 470        FORMAT(A2)
            IF (INCHG .EQ. '1') THEN
                IF (INDMO .EQ. '3') THEN
                    ERROR=0
                    IF (INDTR .EQ. '1') THEN
 471                    WRITE(*,475)
 475                    FORMAT(1X,//,'INPUT NEW REYNOLDS NUMBER')
                        READ(*,480,IOSTAT=ERROR) TRCON
 480                    FORMAT(E10.3)
                        IF (ERROR .GT. 0) THEN
                            GO TO 471
                        END IF
                    ELSE IF(INDTR .EQ. '2') THEN
 481                    WRITE(*,485)
 485                    FORMAT(1X,//,'INPUT NEW "X" TRANSITION'
     1                  'DISTANCE (INCHES)')
                        READ(*,490,IOSTAT=ERROR) TRCON
 490                    FORMAT(E10.3)
                        IF (ERROR .GT. 0) THEN
                            GO TO 481
                        END IF
                    END IF
                ELSE
                    INVALD=1
                END IF
            ELSE IF (INCHG .EQ. '2') THEN
                ERROR=0
 499            WRITE(*,500)
 500            FORMAT(1X,//,'INPUT NEW VALUE OF MOMENTUM THICKNESS'
     1          ' AT THROAT (FEET)')
                READ(*,505,IOSTAT=ERROR) THZERO
 505            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 499
                END IF
            ELSE IF (INCHG .EQ. '3') THEN
                ERROR=0
 509            WRITE(*,510)
 510            FORMAT(1X,//,'INPUT NEW STAGNATION PRESSURE (lbs/in2)')
                READ(*,515,IOSTAT=ERROR) PO
 515            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 509
                END IF
            ELSE IF (INCHG .EQ. '4') THEN
                ERROR=0
 519            WRITE(*,520)
 520            FORMAT(1X,//,'INPUT NEW TOTAL TEMPERATURE (DEGREES R)')
                READ(*,525,IOSTAT=ERROR) TO
 525            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 519
                END IF
            ELSE IF (INCHG .EQ. '5') THEN
```



```
                IF (INDTW .EQ. '1') THEN
                    ERROR=0
 529                WRITE(*,530)
 530                FORMAT(1X,//,'INPUT NEW WALL TEMPERATURE',
     1              '(DEGREES R)')
                    READ(*,535,IOSTAT=ERROR) TWALL
 535                FORMAT(E10.3)
                    IF (ERROR .GT. 0) THEN
                        GO TO 529
                    END IF
                ELSE
                    WRITE(*,540)
 540                FORMAT(1X,//,'INPUT NOT NECESSARY FOR DATA'
     1              ' PREVIOUSLY GIVEN')
                END IF
            ELSE IF (INCHG .EQ. '6') THEN
                ERROR=0
 541            WRITE(*,545)
 545            FORMAT(1X,//,'INPUT NEW EXTENSION LENGTH (INCHES)')
                READ(*,550,IOSTAT=ERROR) XTEND
 550            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 541
                END IF
            ELSE IF (INCHG .EQ. '7') THEN
                ERROR=0
 551            WRITE(*,555)
 555            FORMAT(1X,//,'INPUT NEW "X" INCREMENT (INCHES)')
                READ(*,560,IOSTAT=ERROR) DL
 560            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 551
                END IF
            ELSE IF (INCHG .EQ. '8') THEN
                ERROR=0
 561            WRITE(*,565)
 565            FORMAT(1X,//,'INPUT NEW WIDTH OF NOZZLE (INCHES)')
                READ(*,570,IOSTAT=ERROR) B
 570            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 561
                END IF
            ELSE IF (INCHG .EQ. '9') THEN
                ERROR=0
 571            WRITE(*,575)
 575            FORMAT(1X,//,'INPUT NEW RATIO OF SPECIFIC HEATS')
                READ(*,580,IOSTAT=ERROR) GAMMA
 580            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 571
                END IF
            ELSE IF (INCHG .EQ. '10') THEN
                ERROR=0
 581            WRITE(*,585)
 585            FORMAT(1X,//,'INPUT VISCOSITY-TEMP. EXPONENT')
                READ(*,590,IOSTAT=ERROR) OMEGA
 590            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 581
                END IF
            ELSE IF (INCHG .EQ. '11') THEN
                ERROR=0
 591            WRITE(*,595)
 595            FORMAT(1X,//,'INPUT NEW MOLECULAR WEIGHT')
                READ(*,600,IOSTAT=ERROR) WATE
 600            FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                    GO TO 591
                END IF
            ELSE IF (INCHG .EQ. '12') THEN
                ERROR=0
 601            WRITE(*,605)
 605            FORMAT(1X,//,'INPUT NEW SPECIFIC HEAT (CP- BTU/LB-',
```

```
     1          'DEG-R)')
                READ(*,610,IOSTAT=ERROR) CP
  610           FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                     GO TO 601
                END IF
           ELSE IF (INCHG .EQ. '13') THEN
                ERROR=0
  611           WRITE(*,615)
  615           FORMAT(1X,//,'INPUT NEW PRANDTL NUMBER')
                READ(*,620,IOSTAT=ERROR) PR
  620           FORMAT(E10.3)
                IF (ERROR .GT. 0) THEN
                     GO TO 611
                END IF
           END IF
      COUNT1=COUNT1+1
      GO TO 635
      END IF

C
C     CONVERSION TO INTEGRAL FORMAT
C

      IF (INDMO .EQ. '1') THEN
           INDMO=1
      ELSE IF (INDMO .EQ. '2') THEN
           INDMO=2
      ELSE IF (INDMO .EQ. '3') THEN
           INDMO=3
      END IF

      IF (INDTW .EQ. '1') THEN
           INDTW=1
      ELSE IF (INDTW .EQ. '2') THEN
           INDTW=2
      ELSE IF (INDTW .EQ. '3') THEN
           INDTW=3
      END IF

      IF (INDWC .EQ. '1') THEN
           INDWC=1
      ELSE IF (INDWC .EQ. '2') THEN
           INDWC=2
      ELSE IF (INDWC .EQ. '3') THEN
           INDWC=3
      END IF

      IF (INDTR .EQ. '1') THEN
           INDTR=1
      ELSE IF (INDTR .EQ. '2') THEN
           INDTR=2
      END IF

C
C     END OF KEY BOARD INPUTS
C



      IF(XTEND.LE.X(MAX)) GO TO 640
      DO 645 I=1,600
      NT=I+MAX
      IF(NT.EQ.600) GO TO 650
      X(NT)=X(NT-1)+DL
      YS(NT)=YS(MAX)
      EMS(NT)=EMS(MAX)
      YYS(NT)=YYS(MAX)
      EMES(NT)=EMES(MAX)
      IF(X(NT).GE.XTEND) GO TO 650
  645 CONTINUE
  650 MAX=NT
  640 GO TO (710,710,655), INDTW
```



```
      ERROR=0
  655 WRITE(*,660)
  660 FORMAT(1X,///,'INDICATE THE NUMBER OF TEMPERATURE POINTS TO BE',
     1' ENTERED',/,'THREE OR MORE POINTS ARE REQUIRED OR PROGRAM WILL',
     2' TERMINATE THE DATA OUTPUT PRIOR TO COMPLETION')
      READ(*,665,IOSTAT=ERROR) NUM
  665 FORMAT(I5)
      IF (ERROR .EQ. 0) THEN
           GO TO 655
      END IF
      DO 670 I4=1,NUM
      ERROR=0
  666 WRITE(*,675) 'INPUT THE "X" LOCATION FOR POINT NUMBER ',I4,
     1'RELATIVE TO THE THROAT IN INCHES'
  675 FORMAT(1X,//,A40,I5,/,A32)
      READ(*,680,IOSTAT=ERROR)XXX(I4)
  680 FORMAT(F10.4)
      IF (ERROR .EQ. 0) THEN
           GO TO 666
      END IF
      ERROR=0
  681 WRITE(*,685) 'INPUT TEMPERATURE IN DEGREES R FOR POINT NUMBER',
     1I4
  685 FORMAT(1X,//,A47,I5)
      READ(*,690,IOSTAT=ERROR) TWW(I4)
  690 FORMAT(F10.4)
      IF (ERROR .EQ. 0) THEN
           GO TO 681
      END IF
  670 CONTINUE
      K=1
      DO 695 J=1,MAX
  700 IF(X(J).LT.XXX(K+1)) GO TO 705
      K=K+1
      GO TO 700
  705 TW(J)=TWW(K)+ (X(J)-XXX(K))/(XXX(K+1)-XXX(K))*(TWW(K+1)-TWW(K))
  695 CONTINUE
  710 IF(INDWC.EQ.1) GO TO 715
      IF(LAP.EQ.1) GO TO 725
  715 LAP=2
      DO 720 I=1,MAX
      EME(I)=EMES(I)
      YY(I)=YYS(I)
  720 CONTINUE
      GO TO 735
  725 LAP=1
      DO 730 I1=1,MAX
      EME(I1)=EMS(I1)
      YY(I1)=YS(I1)
  730 CONTINUE
  735 WRITE(26,740)(FMT(I),I=1,10)
  740 FORMAT(1X,20X,10A8,////)
      WRITE(26,745) INDINP,INDPRG,INDMO,INDTW,INDTR,INDWC,INDCF,INDOUT,
     1TRCON,THZERO,PO,TO,TWALL,XTEND,DL,GAMMA,OMEGA,
     2WATE,CP,PR,XINC
  745 FORMAT(1X ,20X,////,30X,'**** INPUT DATA ****',//,32X,
     1'INDINP =',I5,/,32X,'INDPRG =',I5,//,
     115X,'CARD 1',12X,'INDMO =',I5,
     2/,33X,'INDTW =',I5,/,33X,'INDTR =',I5,/,33X,'INDWC =',I5,/,
     233X,'INDCF =',I5,/,32X,'INDOUT =',I5,//,
     315X,'CARD 2',12X,'TRCON =',E15.6,/,32X,'THZERO =',E15.6,
     4/,36X,'PO =',E15.6,/,36X,'TO =',E15.6,/,33X,'TWALL =',E15.6,
     6/,33X,'XTEND =',E15.6,/,36X,'DL =',E15.6,
     8//,15X,'CARD 3',12X,'GAMMA =',E15.6,/,33X,
     5'OMEGA =',E15.6,/,34X,'WATE =',E15.6,/,36X,'CP =',E15.6,
     7/,36X,'PR =',E15.6,/,34X,'XINC =',E15.6)
      PO=PO*144.
      IF (INDTW.EQ.3) GO TO 750
      GO TO 755
  750 WRITE(26,760) NUM
  760 FORMAT(1X,/,15X,'CARD 4',14X,'NUM =',I5)
      DO 765 J1=1,NUM
      NUMB=J1+4
```

Program "nbl6" (cont.)

```
      WRITE (26,770)NUMB,XXX(J1),TWW(J1)
  770 FORMAT(1X,/,15X,'CARD',I3,13X,'XXX =',E15.6,/,35X,'TWW =',E15.6)
  765 CONTINUE
  755 IF(LAP.EQ.2) GO TO 775
      WRITE(26,780)
  780 FORMAT(1X,20X,////,52X,'* WALL DATA *',//,
     136X,'X(IN)',16X,'Y(IN)',16X,'M',//)
      GO TO 785
  775 WRITE(26,790)
  790 FORMAT(1X,20X,////,50X,'* CENTERLINE DATA *',//,
     136X,'X(IN)',16X,'Y(IN)',16X,'M',//)
  785 WRITE(26,795)(X(L),YY(L),EME(L),L=1,MAX)
  795 FORMAT(25X,3E20.6)
      DO 800 I1=1,MAX
      X(I1)=X(I1)/12.0
      YY(I1)=YY(I1)/12.0
  800 CONTINUE
      RETURN
      END



C     SUBROUTINE DATA COMPUTES DM/DS
      SUBROUTINE DATA
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*8, FMT
      DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
     1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
     2DELY(1000),YYY(1000)
      COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
      IF(LAP.EQ.2)GO TO 15
      S(1)=X(1)
      DO 10 I=2,MAX
      S(I)=S(I-1)+SQRT((X(I)-X(I-1))**2+(YY(I)-YY(I-1))**2)
   10 CONTINUE
      GO TO 21
   15 DO 20 I=1,MAX
      S(I)=X(I)
   20 CONTINUE
   21 DO 101 J=1,MAX
   50 FORMAT(20X,I5,3E15.6)
      IF (J.EQ.1) GO TO 91
      IF (J.GE.MAX) GO TO 92
   90 DMDS(J)=(EME(J+1)-EME(J-1))/(S(J+1)-S(J-1))
      GO TO 100
   91 DMDS(J)=(EME(J+1)-EME(J))/(S(J+1)-S(J))
      GO TO 100
   92 DMDS(J)=(EME(J)-EME(J-1))/(S(J)-S(J-1))
  100 IF(DMDS(J).LT.0.0) DMDS(J)=0.0
  101 CONTINUE
      RETURN
       END
      SUBROUTINE CHLOE
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*8, FMT
      DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
     1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
     2DELY(1000),YYY(1000)
      COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
```



```
 1110 SW=TW(N)/TO-1.
 1111 A1=50.71*((ABS (SW))**0.182)-51.8
 1112 B1=1.51-0.722*((ABS (SW))**0.625)
 1113 A2=((7.776*SW+16.125)*SW+7.151)*SW-2.363
 1114 B2=((0.328*SW+0.034)*SW-0.174)*SW+0.73
 1115 C2=2.6*(SW+1.0)
 1116 A3=1.28-1.106*((ABS (SW))**0.964)
 1117 B3=0.903-0.088*((ABS (SW))**4.533)
 1118 GNUE=GMUE/RHOE
 1119 RETURN
       END
      SUBROUTINE LAM IT E
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*8, FMT
      DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
     1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
     2DELY(1000),YYY(1000)
      COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
 1210 ENBAR=((THETA**2)*DUEDS)/(GNUE*TETO)
 1211 HINC=A2*(ENBAR**B2)+C2
 1212 H=HINC/TETO+(TO-TE)/TE
      EN=ENBAR
 1213 EL=A3*(ENBAR**B3)+0.22
 1214 RETH=REL*THETA
 1215 CFOV2=EL/RETH
      CFOV2L=CFOV2
      DDOT=0.
      IF (ENBAR+.3) 10,15,15
   10 D5=-.3
      DDOTND=-28.613546-((14.046635*SW+62.021031)*SW
     $+75.901060)*SW
      DDOT=DDOTND*(ENBAR+.3)
      GO TO 16
   15 D5=ENBAR
   16 DOT=7.9160948+(((30.38170*D5+59.418345*SW+82.319725)*D5+
     1(52.310133*SW+112.21677)*SW+65.130652)*D5+((-14.046635*SW
     2-30.634951)*SW-24.61395)*SW-8.2910568)*D5+(((
     3-.34832207*SW-0.99506674)*SW-.94367191)*SW+2.254166)*SW
      DOT=DOT+DDOT
      THOVDL=1./(DOT+(TO/TE-1.)*(HINC+1.))
      DELRAT=H*THOVDL
 1216 RETURN
       END
      SUBROUTINE TRATUR
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*8, FMT
      DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
     1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
     2DELY(1000),YYY(1000)
      COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
     1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
     2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
     3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
     4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
     5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
     6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
     7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
 1310 RETH=REL*THETA
      GO TO (1311,311),INDCF
  311 ENTURB=0.85*LOG(RETH)-1.29
      GO TO 1312
 1311 ENTURB=.89030368*LOG(RETH)-1.65
 1312 IF(L-4) 1315,1315,1313
 1313 EN=ENTURB
 1314 GO TO 1317
 1315 DELTRE=RETH-RETHTR
```


Program "nbl6" (cont.)

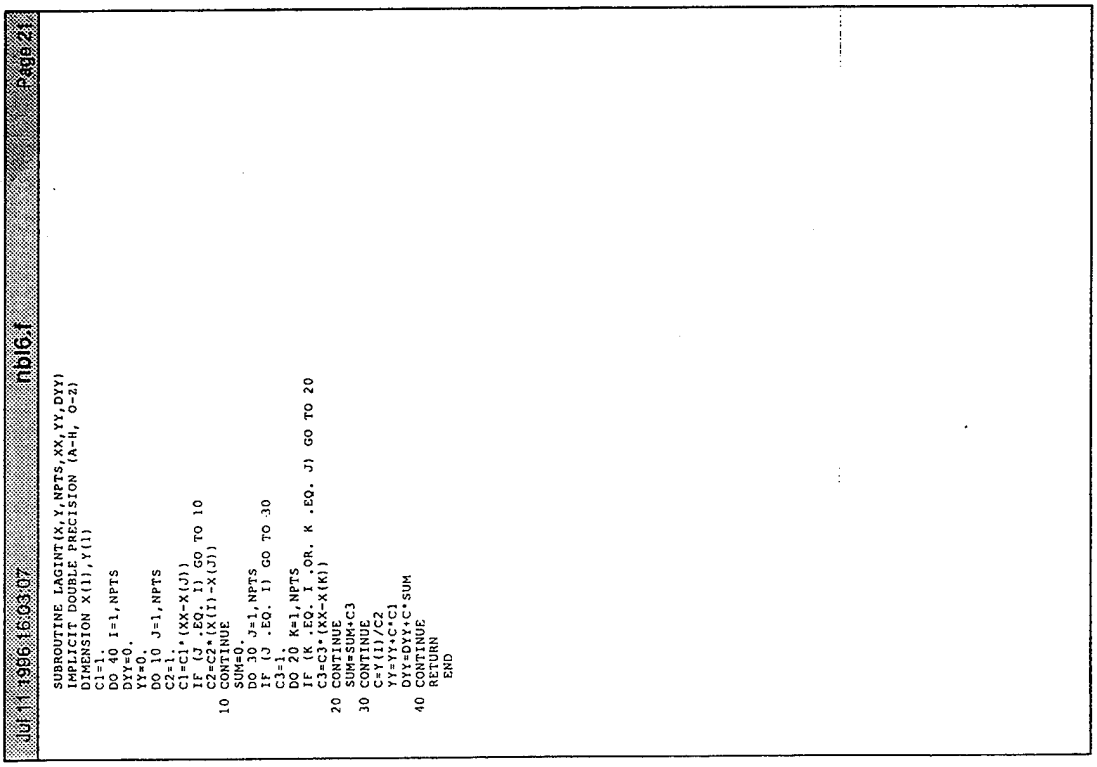
```
1316 EN=((5.25E-3)-(1.9E-6)*DELTRE)*DELTRE+1.25
1317 A=1.-TADTE
1318 B=TADTE-TWTE
1319 POWR=EN
1320 DO 1331 J=1,2
1321 SUM=0.
1322 DO 1324 I=1,16
1323 GIZMO=HALFA(I)*(EXP (XILN(I)*POWR))/((A*XI(I)+B)*XI(I)+TWTE)
1324 SUM=SUM+GIZMO
1325 IF(J-1) 1328,1328,1331
1328 GADGET=EN*SUM
1329 DELRAT=1.-GADGET
1330 POWR=EN+1.
1331 CONTINUE
1332 THOVDL=GADGET-EN*SUM
1333 H=DELRAT/THOVDL
1334 DO 1336 I=1,2
1335 TLTE=1.+.448*(GAMMA-1.)*(EME(N)**2)*(1.-(ULUE**2))+(TWTE-TADTE)*
    1      (1.-ULUE)
1336 ULUE=(20.*EN*THOVDL*(TLTE**(1.+OMEGA))/RETH)**(1./(EN+1.))
     GO TO (1337,337),INDCF
 337 CFOV2=.002205*TETO**0.5*(TWTE/TADTE)**0.345/RETH**0.1
     GO TO 1338
1337 CFOV2=((20.*ENTURB)**((1.-ENTURB)/(1.+ENTURB)))*((THOVDL/RETH)
    1  **(2./(ENTURB+1.)))*(TLTE**((1.+2.*OMEGA-ENTURB)/(ENTURB+1.)))
1338 IF(L-4) 1339,1342,1343
1339 QUAY=(CFOV2-CFOV2L)*(RETH**2)
1340 GO TO 1343
1342 CFOV2=CFOV2-QUAY/(RETH**2)
1343 RETURN
      END
     SUBROUTINE OUT
     IMPLICIT DOUBLE PRECISION (A-H, O-Z)
     CHARACTER*8, FMT
     DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
    1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
    2DELY(1000),YYY(1000)
     COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
    1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
    2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
    3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
    4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
    5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
    6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
    7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
     XCOR=X(N)*12.
     SCOR=S(N)*12.
     YCOR=YY(N)*12.
     BCLAUS=THETA/TAUWAL*DPDS
     THEIN=THETA*12.
     DELSIN=DELTA*12.
     DELIN=THEIN/THOVDL
     TWTAD=TW(N)/TAD
     TWTO=TW(N)/TO
     TADTO=TAD/TO
     CF=CFOV2*2.
     IF(N.GT.MIN) GO TO 12
     WRITE(26,4)
   4 FORMAT(1X,19X,////,56X,'*** OUTPUT CODE ***',///)
     WRITE(26,5)
   5 FORMAT(20X,'X(IN)',10X,'S(IN)',10X,'Y(IN)',12X,'M',10X,
    1'REL(1/FT)',8X,'RETH',11X,'PE/PO',///)
     WRITE(26,6)
   6 FORMAT(17X,'UE(FT/SEC)',4X,'MUE(PSEC/FT2)',1X,'RHOE(PSEC2/FT4)',
    15X,'TE(R)',10X,'TW(R)',9X,'TAD(R)',10X,'TE/TO',///)
     WRITE(26,7)
   7 FORMAT(18X,'DELTA(IN)',6X,'THETA(IN)',6X,'DELSTAR(IN)',9X,'H',11X
    1,'TW/TO',10X,'TW/TAD',10X,'TAD/TO',///)
     WRITE(26,8)
   8 FORMAT(17X,'DPDS(P/FT2)',4X,'DMDS(1/FT)',7X,'DUDS(1/SEC)',6X,
    1'DTHDS',6X,'TAUWAL(P/FT2)',7X,'CF',11X,'BETATH',///)
     WRITE(26,9)
   9 FORMAT(16X,'Q(BTU/FT2/SEC)',1X,'HA(BTU/FT2SECR)',8X,'N',///)
```



```
    12 IF (L-4)13,18,22
    13 WRITE(26,15)N,IT
    15 FORMAT(1X,//,15X,'POINT NO.',I4,4X,'LAMINAR',5X,I3,1X,
      1'ITERATIONS')
       GO TO 30
    18 WRITE(26,20)N,IT
    20 FORMAT(1X,//,15X,'POINT NO.',I4,4X,'TRANSITION',5X,I3,1X,
      1'ITERATIONS')
       GO TO 30
    22 WRITE(26,25)N,IT
    25 FORMAT(1X,//,15X,'POINT NO.',I4,4X,'TURBULENT',5X,I3,1X,
      1'ITERATIONS')
    30 WRITE(26,35)XCOR,SCOR,YCOR,EME(N),REL,RETH,POVPO(N),UE,GMUE,RHOE,
      1TE,TW(N),TAD,TETO, DELIN,THEIN,DELSIN,H,TWTO,TWTAD,TADTO,DPDS,
      1DMDS(N),DUEDS,DTHDS,TAUWAL,CF,BCLAUS,DHEAT,HA,EN
    35 FORMAT(15X,7E15.6)
       IT=0
       RETURN
        END
       SUBROUTINE IPSO
       IMPLICIT DOUBLE PRECISION (A-H, O-Z)
       CHARACTER*8,FMT
       DIMENSION X(1000),YY(1000),EME(1000),HALFA(16),XI(16),XILN(16),
      1TW(1000),S(1000),POVPO(1000),DMDS(1000),FMT(10),
      2DELY(1000),YYY(1000)
       COMMON CFOV2,CFOV2L,CFOV2T,DELRAT,DELTA,DELTRE,DELTTH,DHEAT,DTHDS
      1,DUEDS,EN,ENBAR,ENTURB,H,HINC,OLDDTH,REL,RETH,RETHTR,RHOE,THETA,
      2TAUWAL,THBAR,THETA2,THOVDL,TLTE,ULUE,TRCON,THZERO,PO,TO,TWALL,
      3GAMMA,OMEGA,WATE,CP,PR,GMUO,SW,A1,B1,A2,B2,C2,A3,B3,GNUE,TE,TAD,
      4TADTE,TWTE,QUAY,TETO,UE,GMUE,HA,DPDS,DL,XINC,X(1000),YY(1000),
      5EME(1000),HALFA(16),XI(16),XILN(16),TW(1000),S(1000),POVPO(1000),
      6DMDS(1000),FMT(10),IT,L,N,LINES,KOUNT,LAP,NN,INDCF,INDMO,INDMU,
      7INDTW,INDTR,INDWC,MAX,MIN,INDINP,INDOUT,ITMES,INDPRG
  1610 IT=0
       GO TO (1614,1614,1624,1624,1647,1647),L
  1614 L=2
       IF (INDTR.EQ.2) GO TO 1616
  1615 IF(TRCON-RETH) 1618,1618,1642
  1616 IF(TRCON-X(N)) 1618,1618,1642
  1618 L=3
  1620 RETHTR=RETH
  1621 ULUE=1.0E-4
  1622 CFOV2L=CFOV2
  1623 GO TO 1642
  1624 L=4
       IF(1600.-DELTRE)1647,1647,1642
  1647 L=5
  1642 RETURN
        END
       SUBROUTINE SETXEQ(XW,NO,XL,SML,NEND)
       IMPLICIT DOUBLE PRECISION (A-H, O-Z)
       DIMENSION XW(600),XL(600),SML(600),SMM(600)
       DO 70 J=1,600
       JT=J
       IF (XL(J).GE.XW(NO) ) GO TO  71
    70 CONTINUE
    71 K=JT
       KEND=NEND-3
       DO 40 I=NO,NEND
     5 IF(XW(I).LE.XL(K)) GO TO 10
       K=K+1
       GO TO 5
    10 IF(K.LE.KEND) GO TO 20
       GO TO 30
    20 CALL LAGINT(XL(K-2),SML(K-2),5,XW(I),SMM(I),DYO)
       GO TO 40
    30 CALL LAGINT(XL(K-4),SML(K-4),5,XW(I),SMM(I),DYO)
    40 CONTINUE
       DO 60 J=NO,NEND
       SML(J)=SMM(J)
    60 CONTINUE
       RETURN
        END
```


Program "nbl6" (cont.)

Program "nbl6" (cont.)



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```
      SUBROUTINE LAGINT(X,Y,NPTS,XX,YY,DYY)
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      DIMENSION X(1),Y(1)
      C1=1.
      DO 40 I=1,NPTS
      DYY=0.
      YY=0.
      DO 10 J=1,NPTS
      C2=1.
      C1=C1*(XX-X(J))
      IF (J .EQ. I) GO TO 10
      C2=C2*(X(I)-X(J))
   10 CONTINUE
      SUM=0.
      DO 30 J=1,NPTS
      IF (J .EQ. I) GO TO 30
      C3=1.
      DO 20 K=1,NPTS
      IF (K .EQ. I .OR. K .EQ. J) GO TO 20
      C3=C3*(XX-X(K))
   20 CONTINUE
      SUM=SUM+C3
   30 CONTINUE
      C=Y(I)/C2
      YY=YY+C*C1
      DYY=DYY+C*SUM
   40 CONTINUE
      RETURN
      END
```

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